Neutrino mass, lepton number, and the origin of matter

1. Major scientific discoveries since 2007.

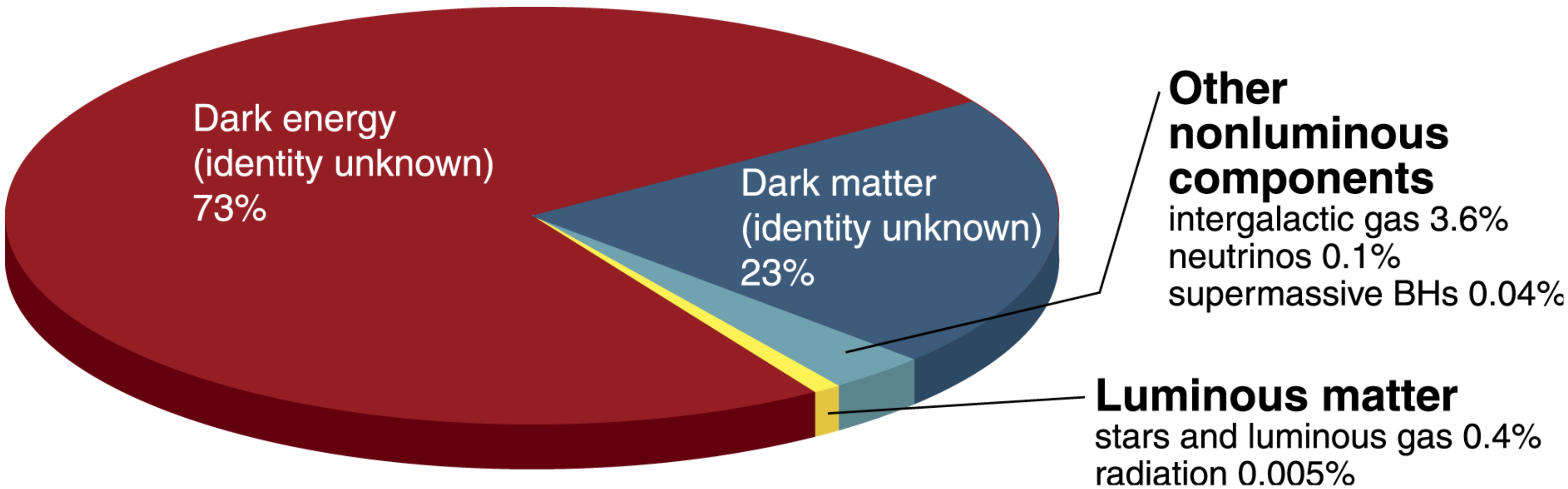
2. Compelling and unique science to be done in the next 5 years and through 2020.

3. Strategic planning issues:

SURF, Double Beta Decay, Connection to HEP, Community ”voice”.

Hamish Robertson, DNP Town Meeting, Oct. 25, 2012

The Universe -- A very odd place



And why is there **matter** but no **antimatter**?

Sakharov's criteria:

Baryon number not conserved…

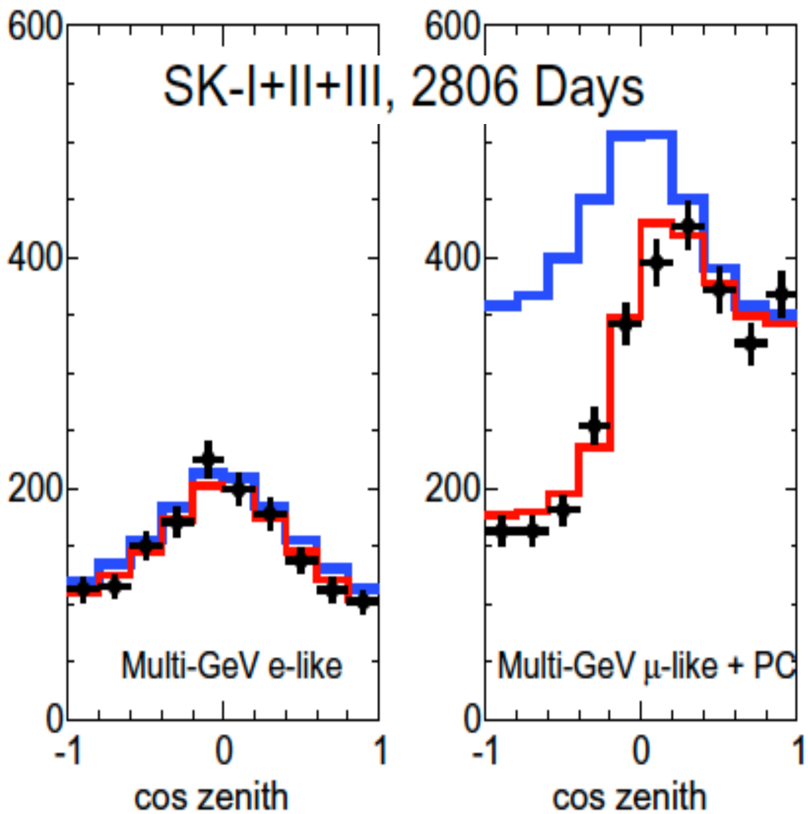
CP violated…

Universe not in equilibrium at some point…

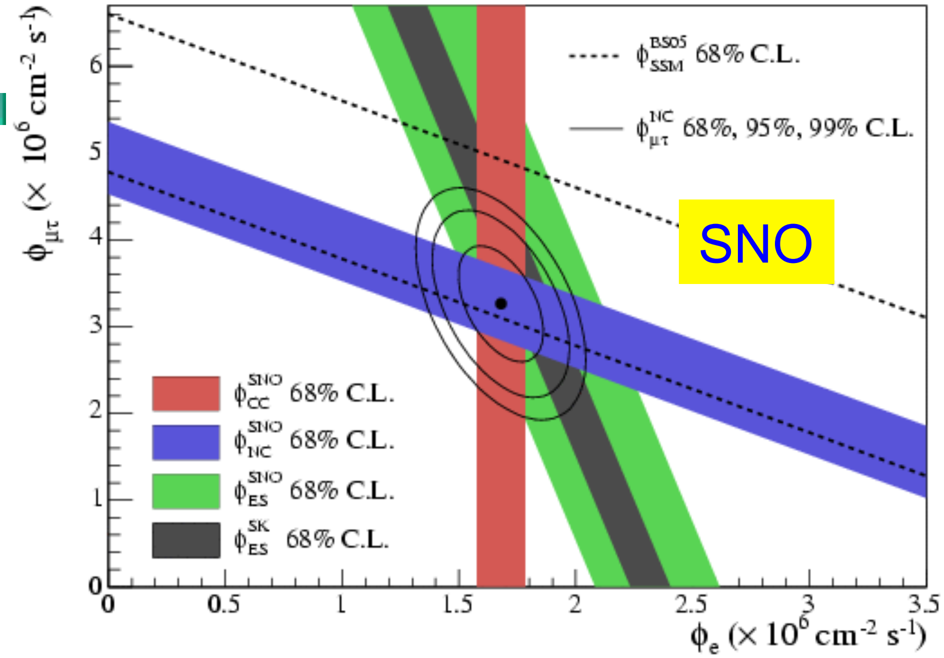
Major scientific discoveries since 2007

- θ_{13} measured!
- Higgs found!
- Borexino, SNO, SK, KamLAND results
- MiniBooNE results
- Nuclear theory of DBD
- EXO and KamLAND results for ^{136}Xe $2\nu\beta\beta$, $0\nu\beta\beta$
- Idea to use cyclotron radiation for neutrino mass measurement

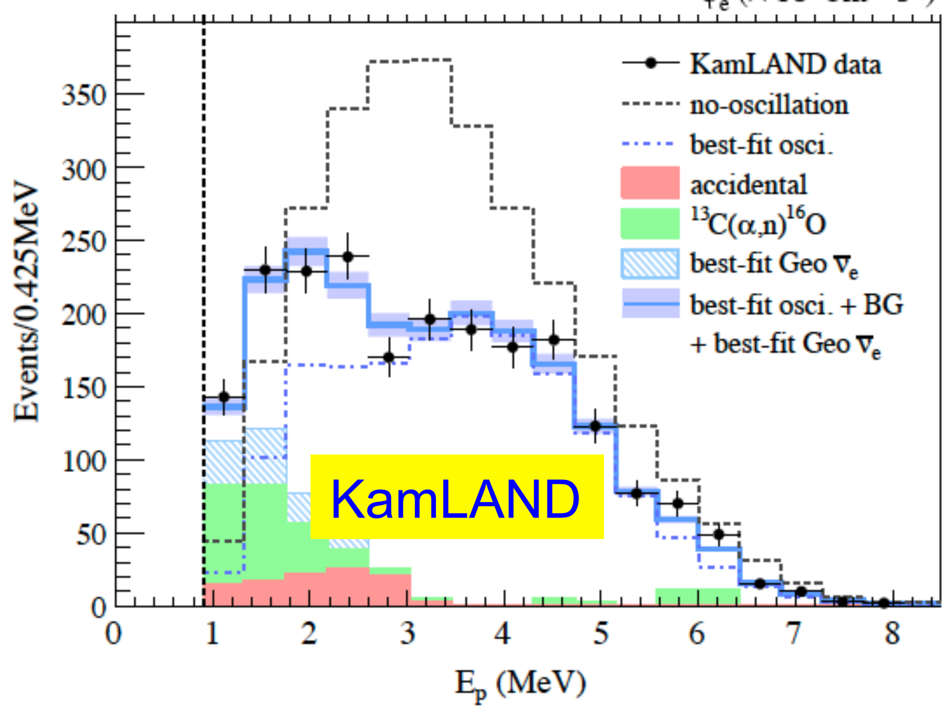
Neutrinos oscillate, have mass



Super-Kamiokande

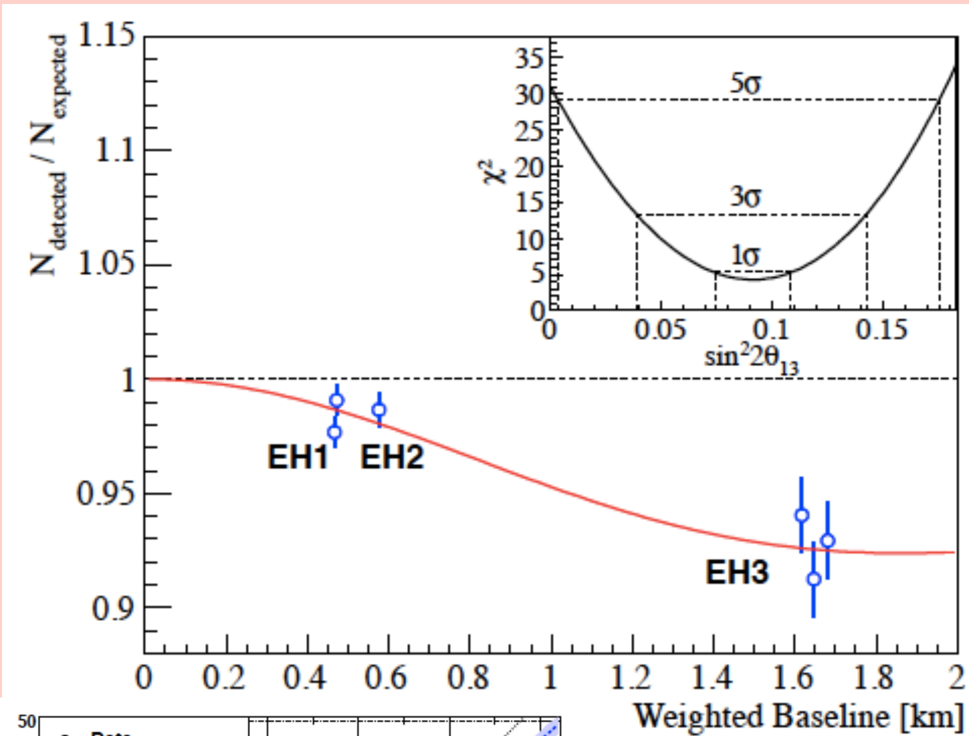


SNO

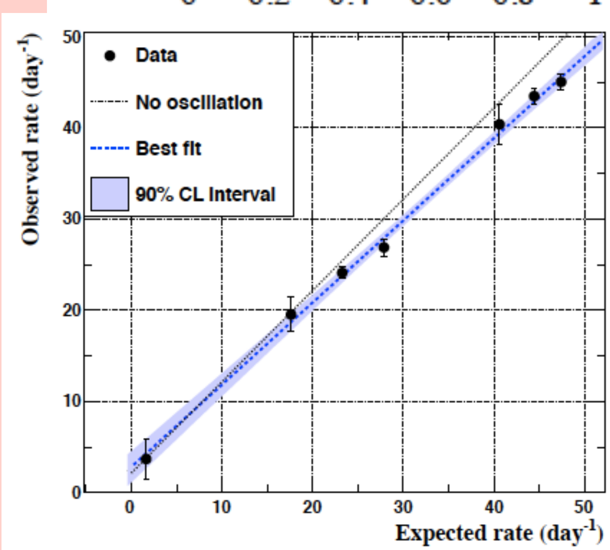


KamLAND

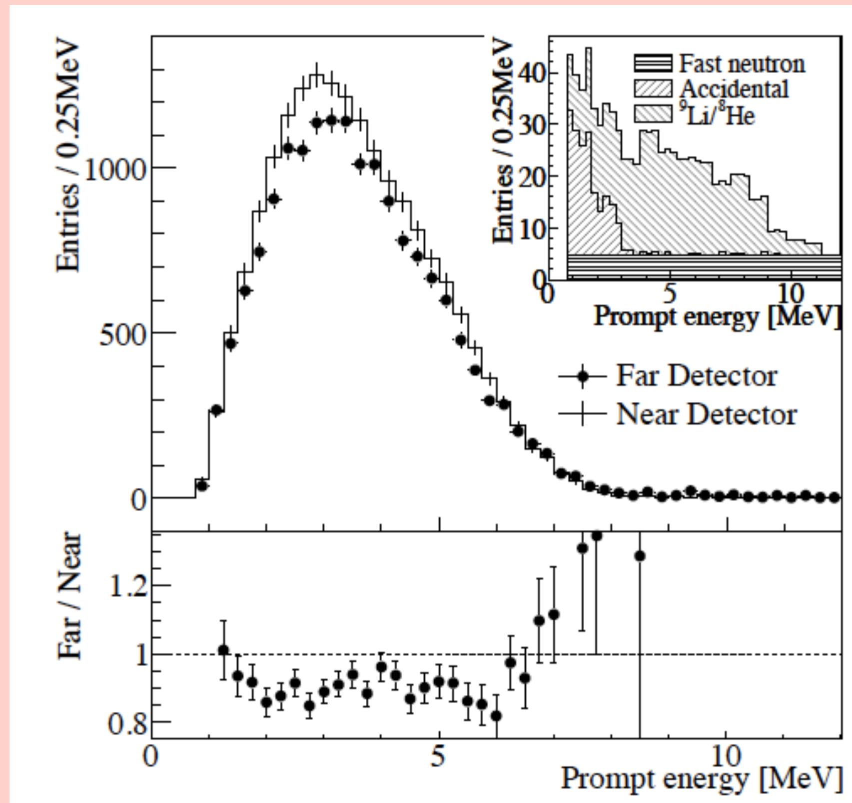
Θ_{13} Measured!



Daya Bay



Double Chooz



RENO

Mass and mixing parameters

	Oscillation	Kinematic
Δm_{21}^2	$7.54^{+0.21}_{-0.21}$ x 10^{-5} eV^2	
$\|\Delta m_{32}^2\|$	$2.42^{+0.12}_{-0.11}$ x 10^{-3} eV^2	
Σm_i	> 0.055 eV (90% CL)	< 5.4 eV (95% CL)*
θ_{12}	$34.1^{+0.9}_{-0.9}$ deg	
θ_{23}	$39.2^{+1.8}_{-1.8}$ deg	
θ_{13}	$9.1^{+0.6}_{-0.7}$ deg	
$\sin^2\theta_{13}$	$0.025^{+.003}_{-.003}$	

Marginalized 1-D 1-σ uncertainties.

*C. Kraus et al., Eur. Phys. J. C40, 447 (2005); V. Aseev et al. PRD in press.
Other refs, see Fogli et al. 1205.5254

What do we still want to know?

Are neutrinos their own antiparticles?

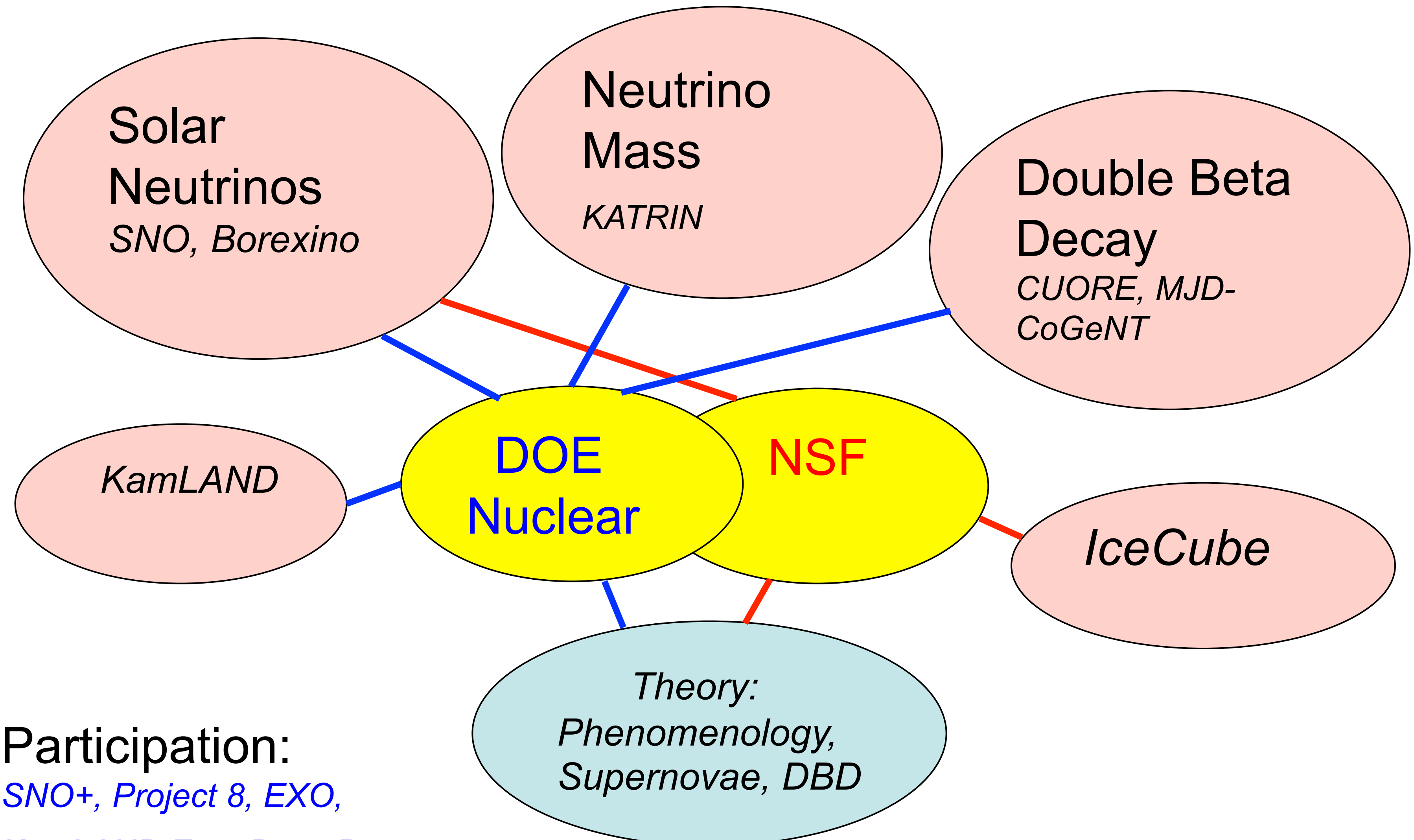
Do neutrinos violate CP?

What is the mass?

What is the level ordering (hierarchy)?

And many other things…

The Neutrino Portfolio in DOE-NP and NSF



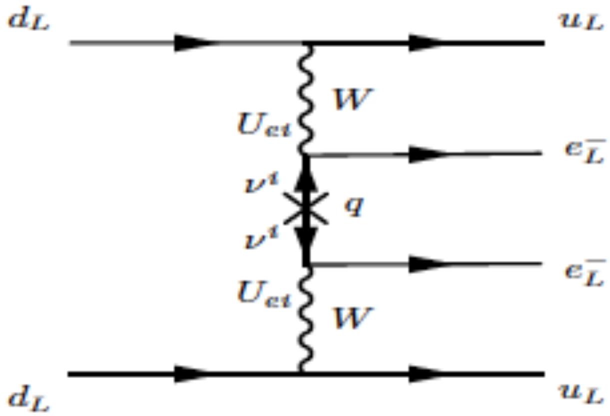
Participation:

SNO+, Project 8, EXO,

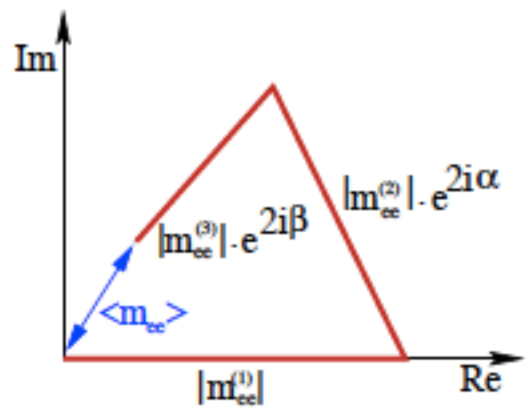
KamLAND-Zen, Daya Bay,

Neutrinoless Double Beta Decay

Are neutrinos their own antiparticles?
Is lepton number conserved?



W. Rodejohann, 1206.2560



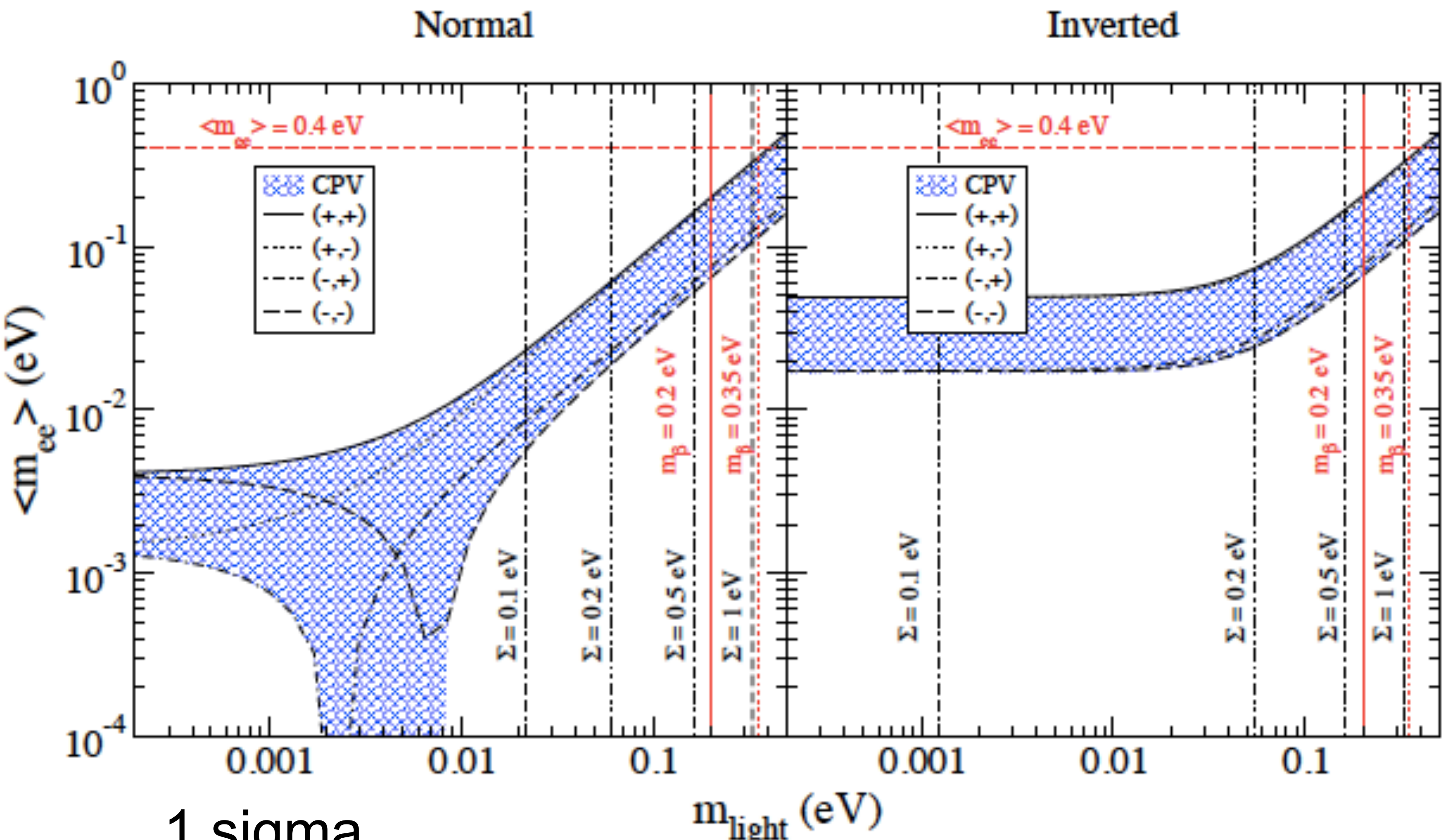
Decay rate per unit mass:

$$\lambda_{0\nu} \frac{N}{M} = \frac{\ln(2) N_A}{A m_e^2} G_{0\nu}^{(0)} g_A^4 |M_{0\nu}|^2 |\langle m_{ee} \rangle|^2$$

$$\equiv \Gamma_{0\nu} \, |M_{0\nu}|^2 \, |\langle m_{ee} \rangle|^2$$

$$\langle m_{ee} \rangle = \left| U_{e1}^2 m_1 + U_{e2}^2 m_2 e^{i\alpha} + U_{e3}^2 m_3 e^{i\beta} \right|$$

Neutrinoless Double Beta Decay

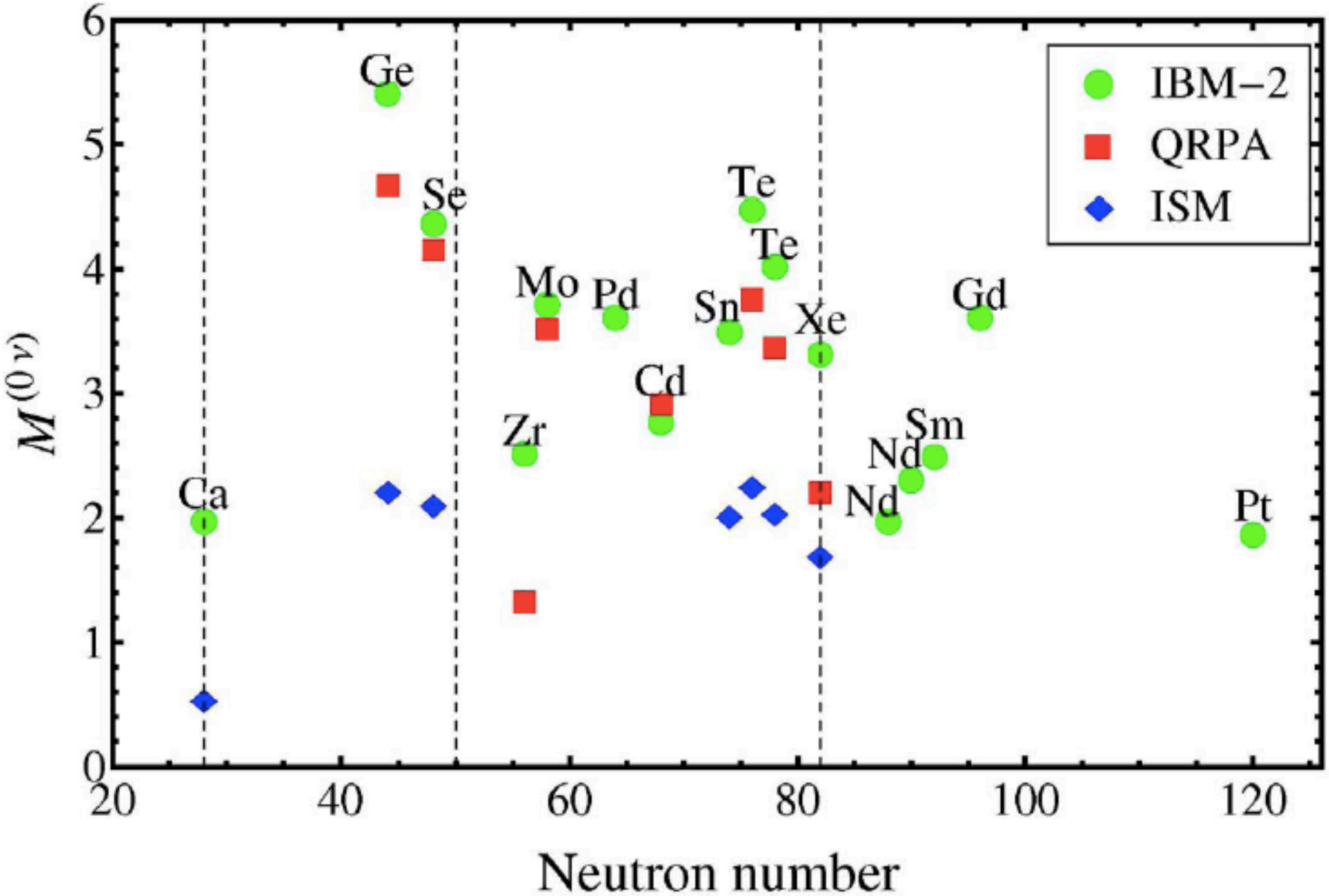


1 sigma

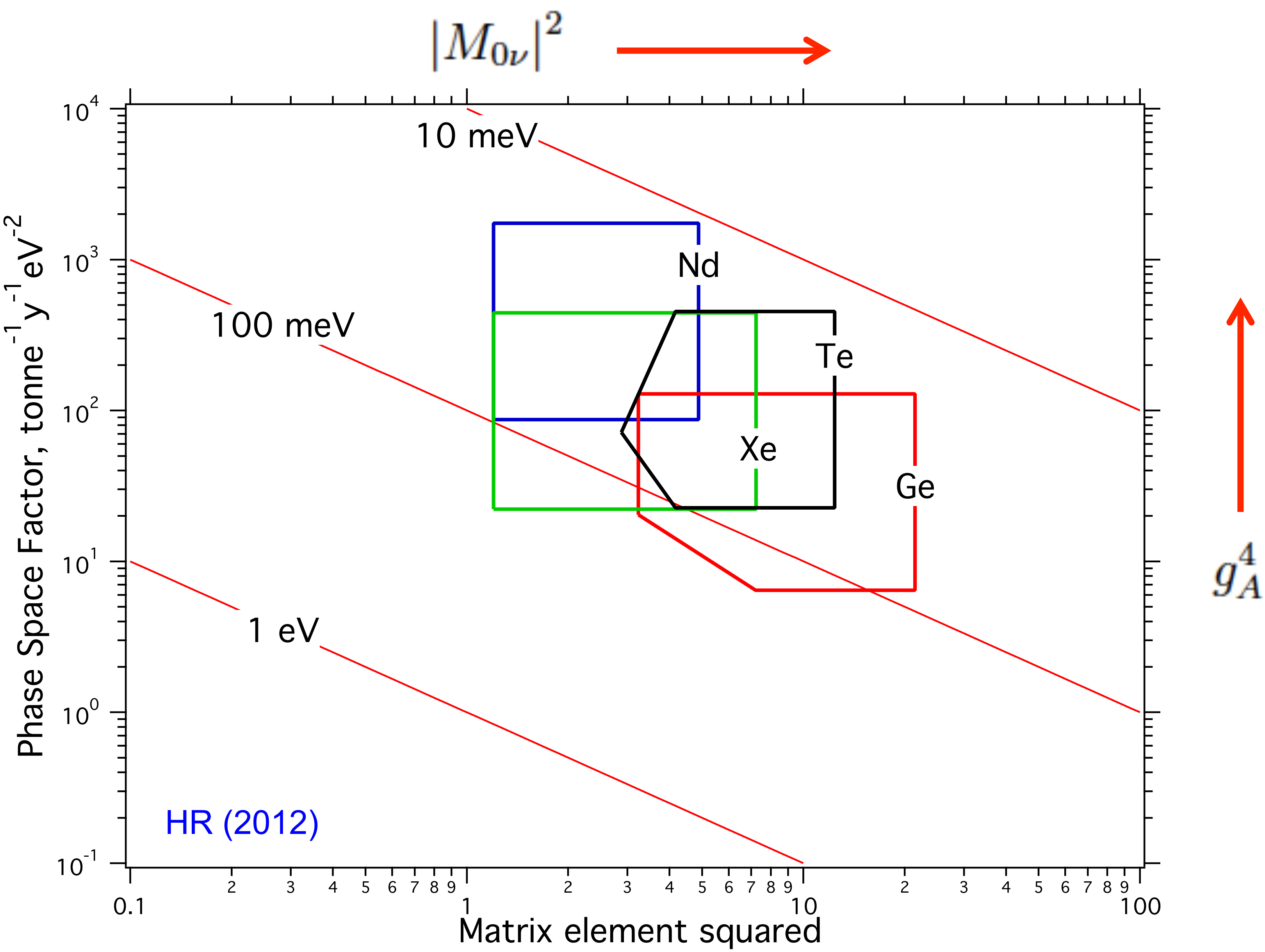
W. Rodejohann, 1206.2560

IBM-2 RESULTS (JAN 2012)
LIGHT NEUTRINO EXCHANGE

F. Iachello

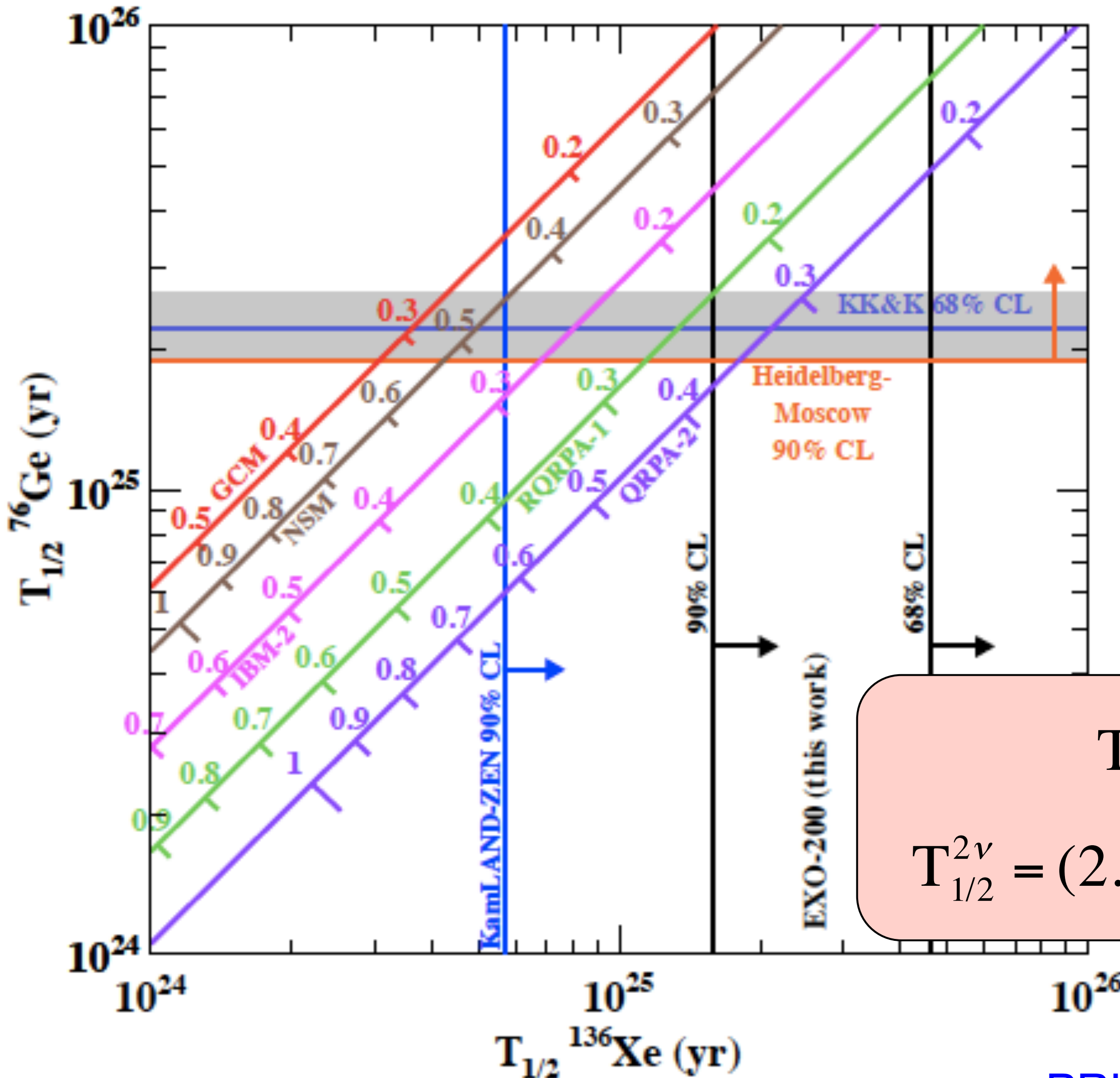


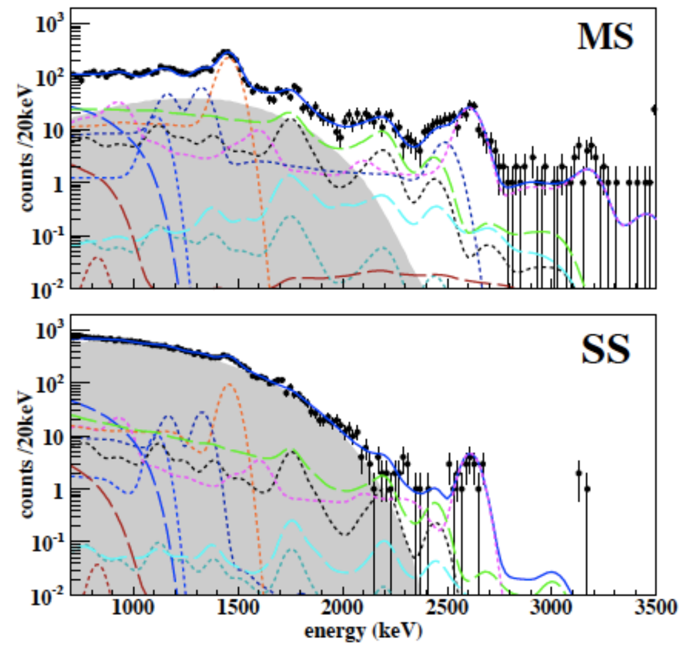
IBM-2 from J. Barea and F. Iachello, Phys. Rev. C 79, 044301 (2009) and to be published.
QRPA from F. Šimkovic *et al.*, Phys. Rev. C 77, 045503 (2008).
ISM from E. Caurier *et al.*, Phys. Rev. Lett. 100, 052503 (2008).



Regions contain calculated matrix elements (SM, QRPA, IBM, GCM) and range of g_A values (free nucleon down to 2νββ fits).

EXO measures ^{136}Xe 2νββ, limits 0νββ



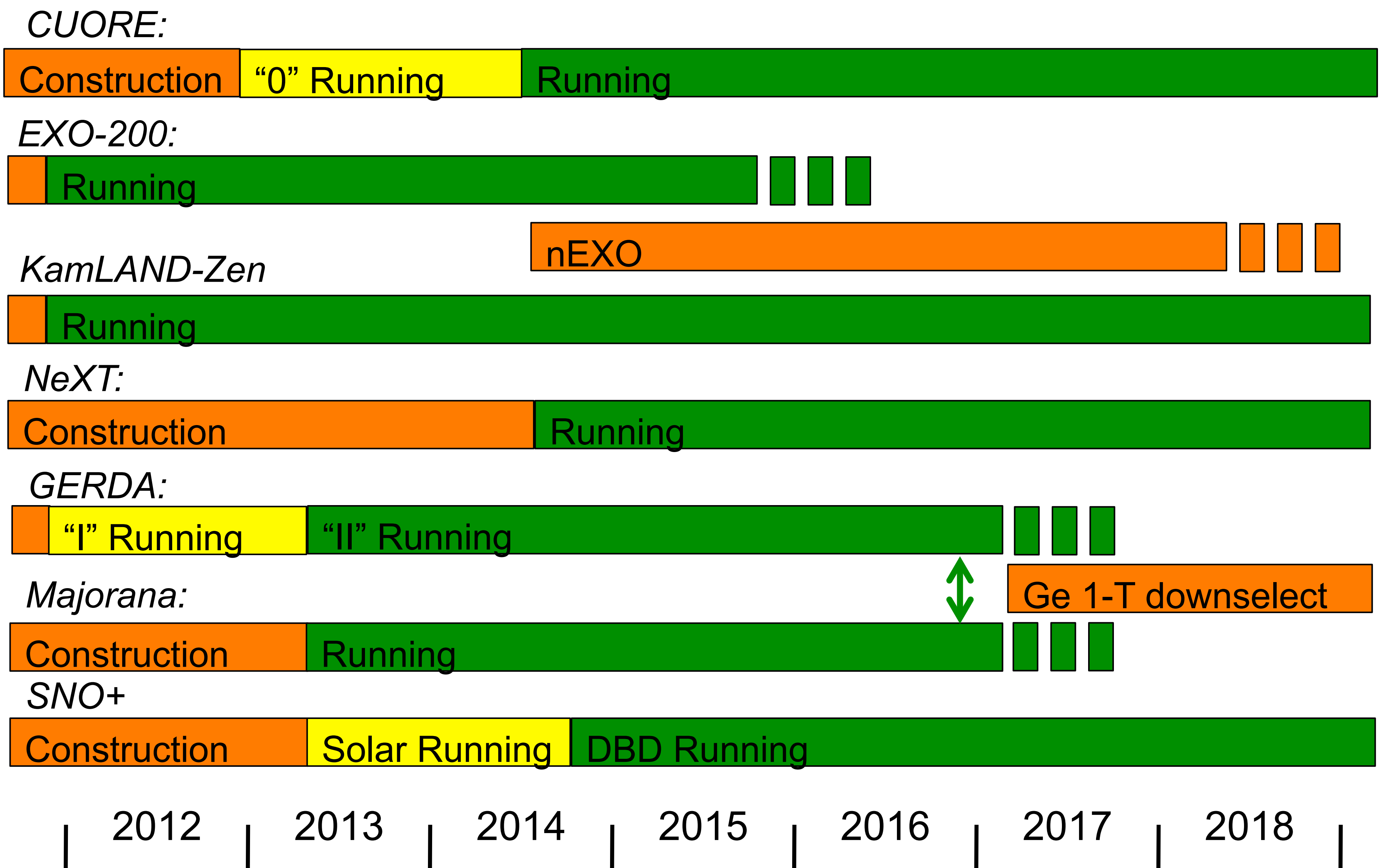


$$T_{1/2}^{0\nu} \geq 1.6 \times 10^{25} \quad \text{yr}$$

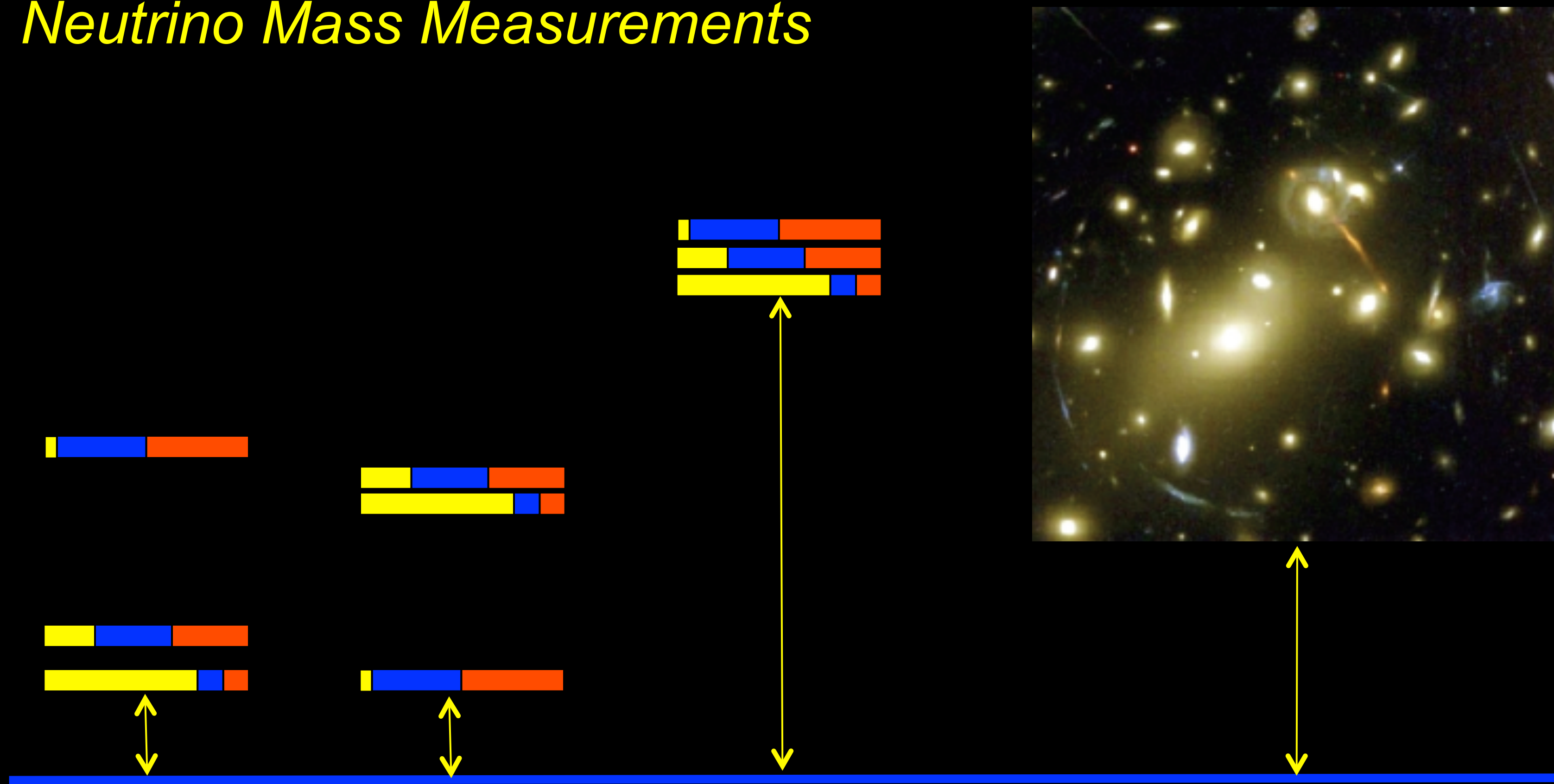
$$T_{1/2}^{2\nu} = (2.23 \pm 0.017 \pm 0.22) \times 10^{21} \quad \text{yr}$$

PRL 109, 032505 (2012)

Double Beta Decay: some milestones



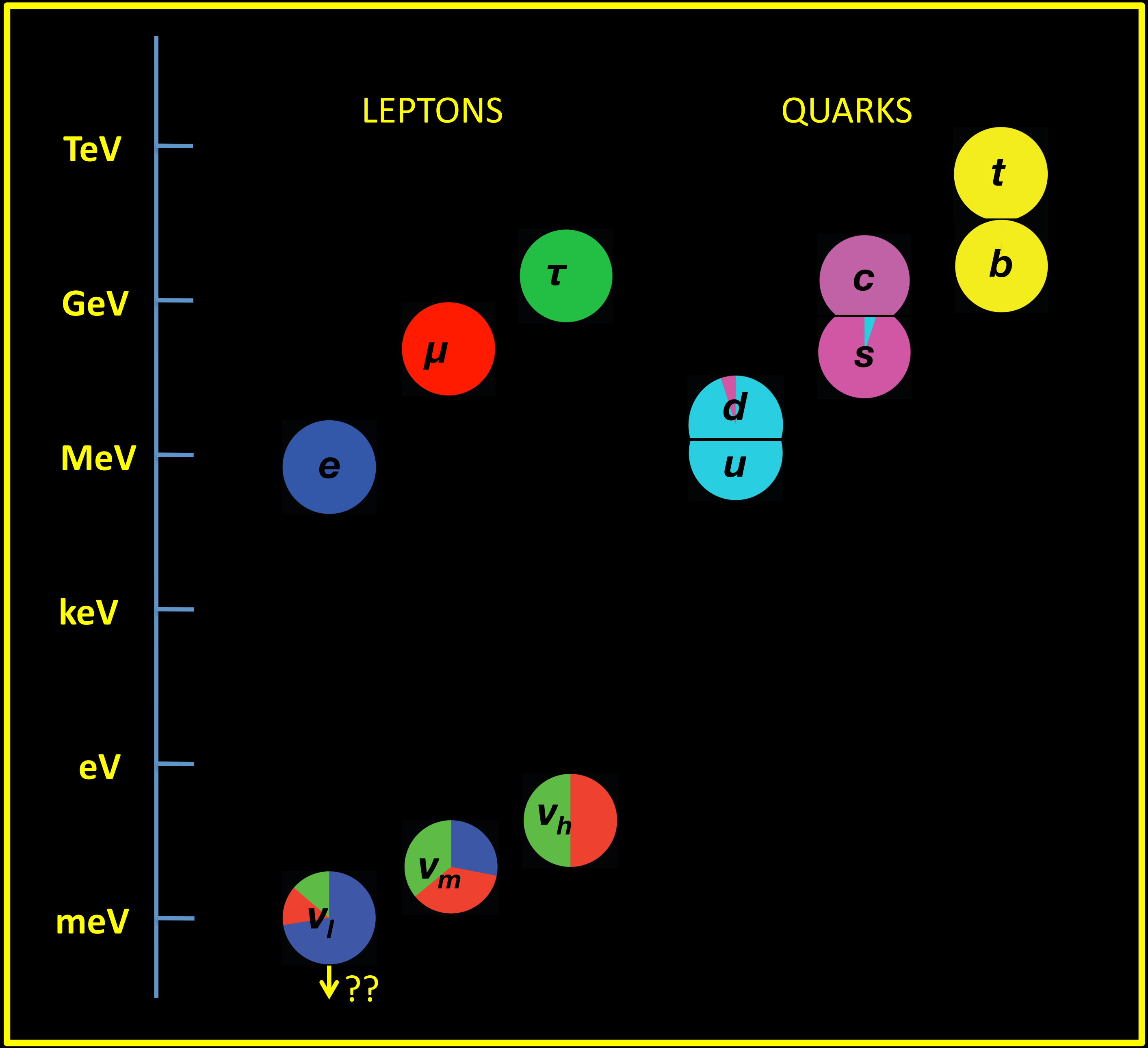
Neutrino Mass Measurements



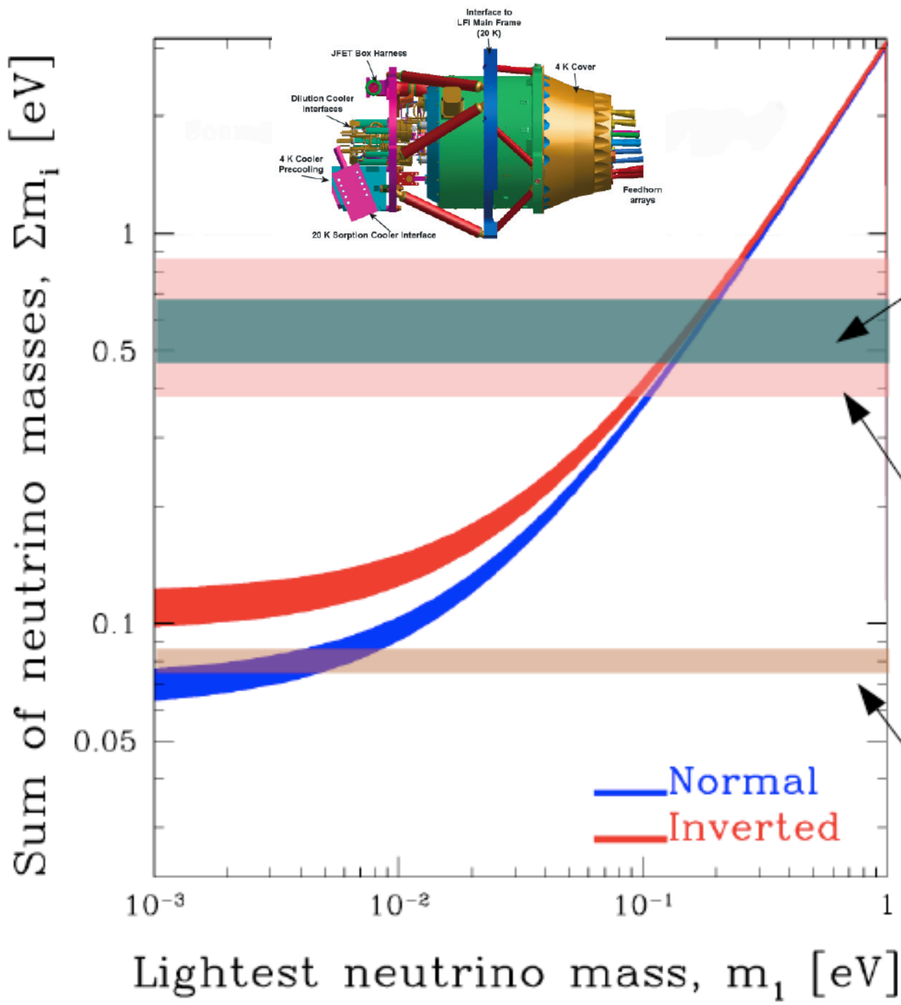
Particle Physics

Cosmology

What is the neutrino mass scale?


LEPTONS
QUARKS
TeV
GeV
MeV
keV
eV
meV
τ
μ
e
t
b
c
s
d
u
ν_h
ν_m
ν_l
??

Present constraints and future sensitivities...



CMB (WMAP7+ACBAR+BICEP+QuaD)
+ LSS (SDSS-HPS)
+ HST+SNIa

$$\sum m_\nu < 0.44 \rightarrow 0.76\,\mathrm{eV} \quad (95\%\,\mathrm{CI})$$

depending on the model complexity

Hannestad, Mirizzi, Raffelt & Y³W 2010
Gonzalez-Garcia et al. 2010, etc.

Planck alone (1 year)

$$\sum m_\nu < 0.38 \rightarrow 0.84\,\mathrm{eV} \quad (95\%\,\mathrm{CI})$$

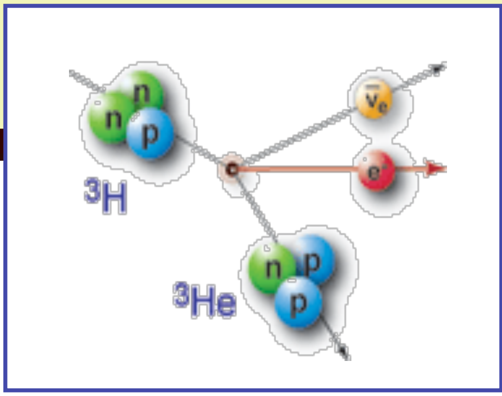
Perotto et al. 2006

Planck+Weak lensing (LSST)

$$\sum m_\nu < 0.074 \rightarrow 0.086\,\mathrm{eV} \quad (95\%\,\mathrm{CI})$$

Hannestad, Tu & Y³W 2006

Neutrino mass from Beta Spectra



With flavor mixing:

$$\frac{dN}{dT} = \frac{G_F \cos\theta_C}{2\pi^3} |M_{\text{nuc}}|^2 F(Z,T)(T+m)(T^2+2mT)^{1/2}(T_0-T)\sum_i |U_{ei}|^2 \left[(T_0-T)^2 - m_i^2\right]^{1/2}$$

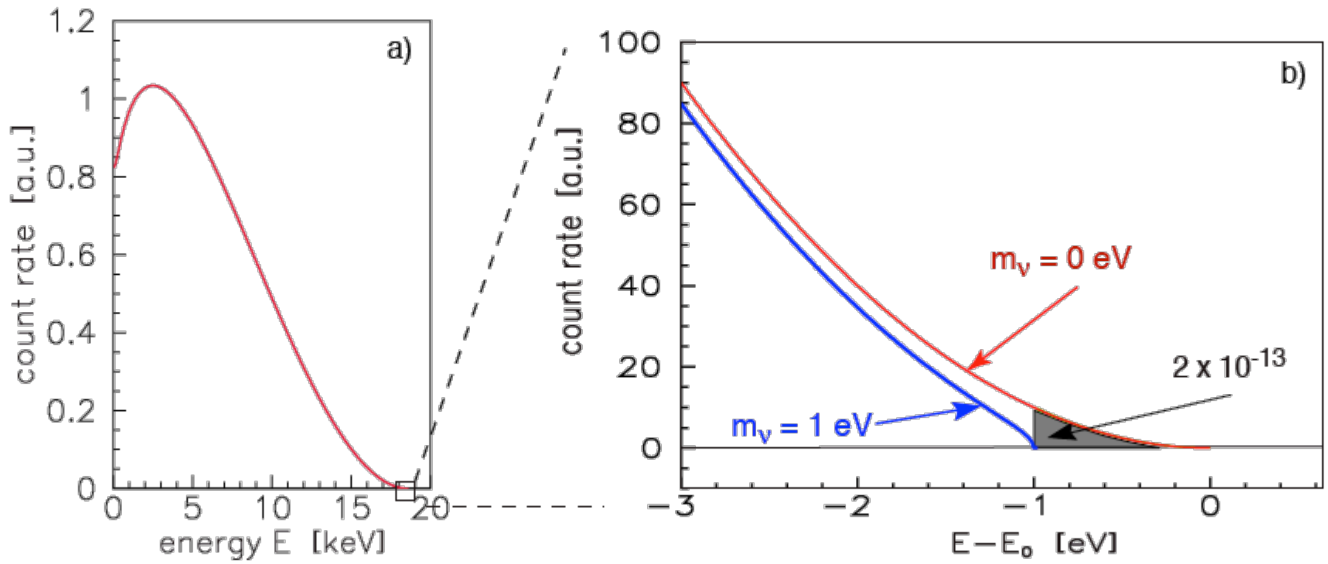
$$m_i^2 = \Delta m_{i0}^2 + m_0^2$$

mixing

neutrino masses

from oscillations

mass scale

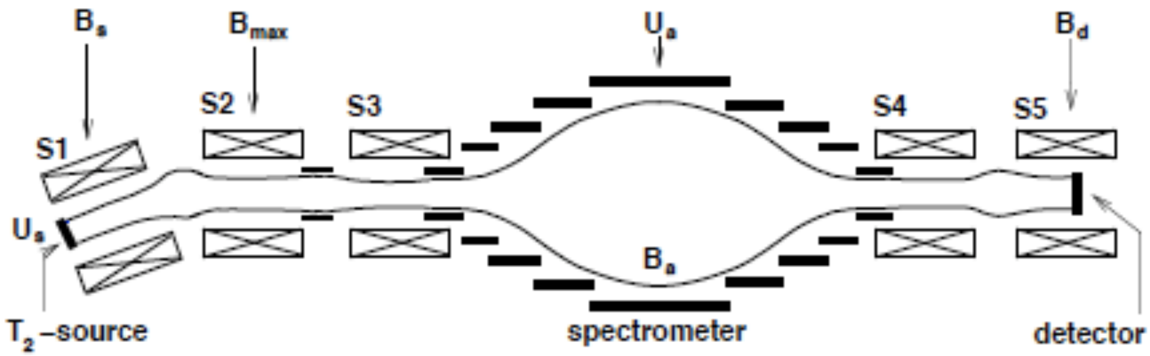


Current status of direct mass measurement

Mainz: solid T_2, MAC-E filter

C. Kraus et al., Eur. Phys. J. C40, 447 (2005)

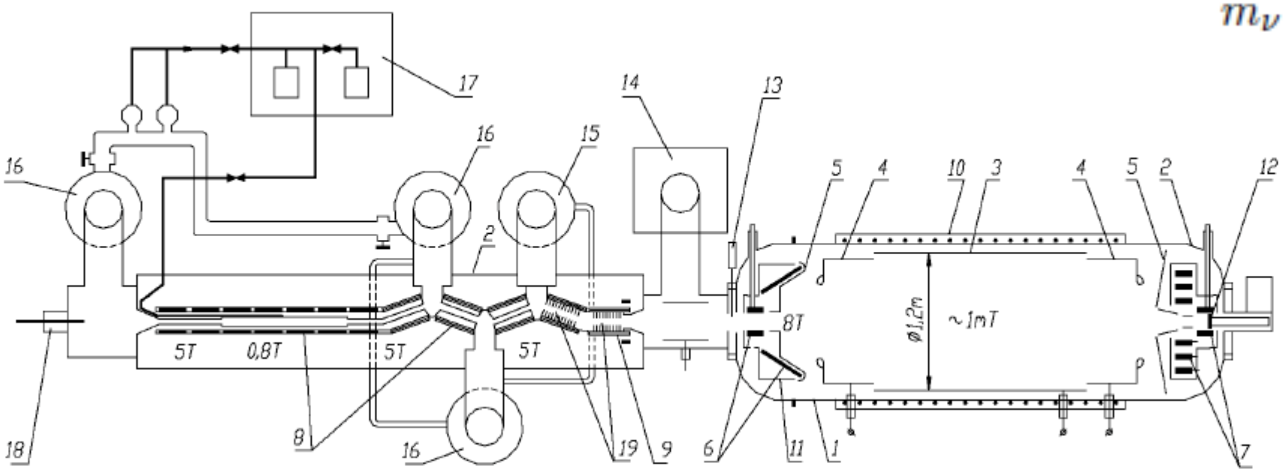
$$m^2(\nu_e) = (-0.6 \pm 2.2_{\text{stat}} \pm 2.1_{\text{syst}})$$
$$m(\nu_e) < 2.3\ \text{eV/c}^2 \quad (95\%\ \text{C.L.})$$



Troitsk: gaseousT_2, MAC-E filter

V. Aseev et al., PRD in press (2011)

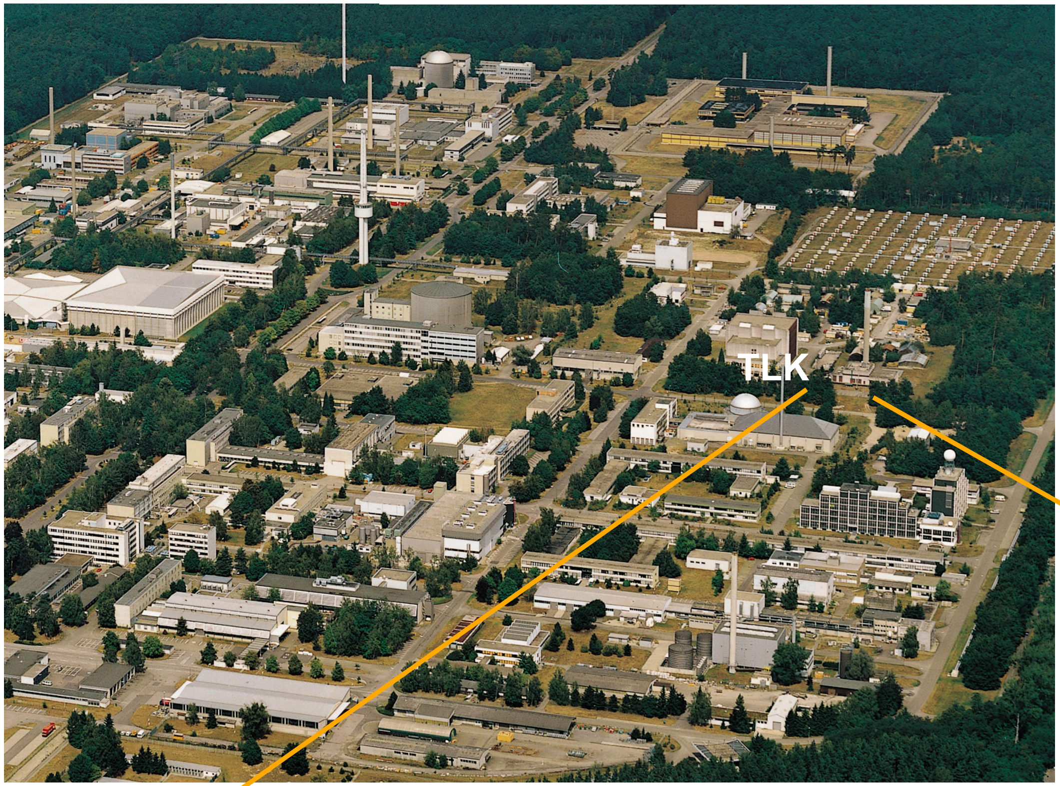
$$m_\nu^2 = -0.67 \pm 1.89_{stat} \pm 1.68_{syst}$$
$$m_\nu < 2.05\, eV,\ 95\%\ C.L.$$



Together:…
$m_\nu < 1.8$ eV
(95% CL)

KATRIN

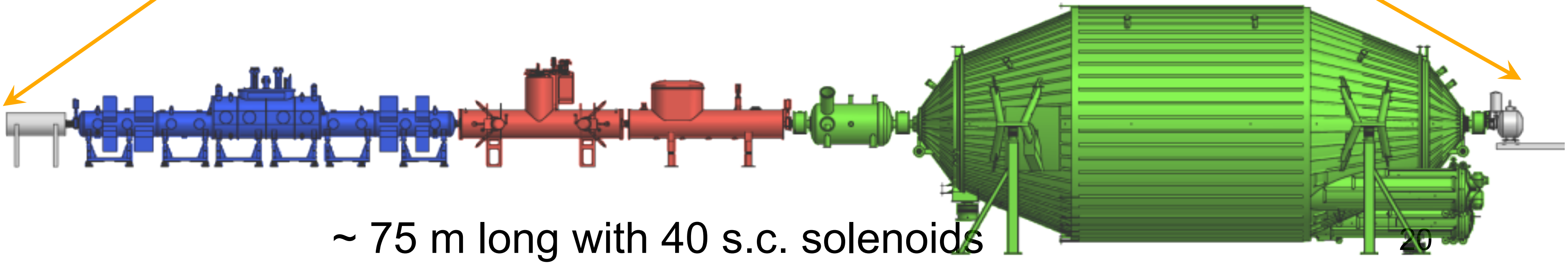
At Karlsruhe Institute of Technology
unique facility for closed T_2 cycle:
Tritium Laboratory Karlsruhe



Size of experiment now:
Diameter 10 m.

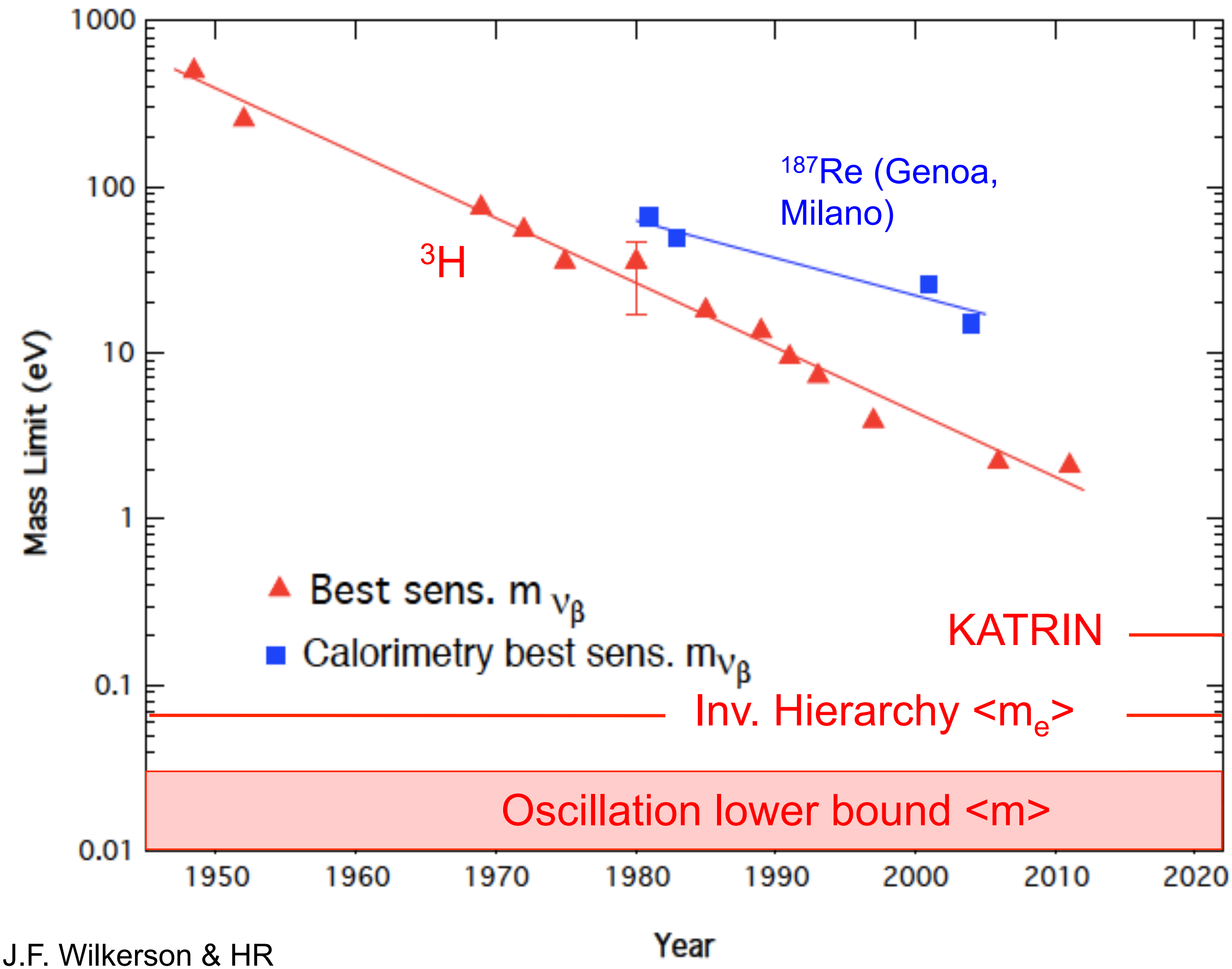
$$\sigma(m_\nu^2) = k\frac{b^{1/6}}{r^{2/3}t^{1/2}},$$

Next diameter: 300 m!



~ 75 m long with 40 s.c. solenoids

Neutrino Mass Limits from β decay



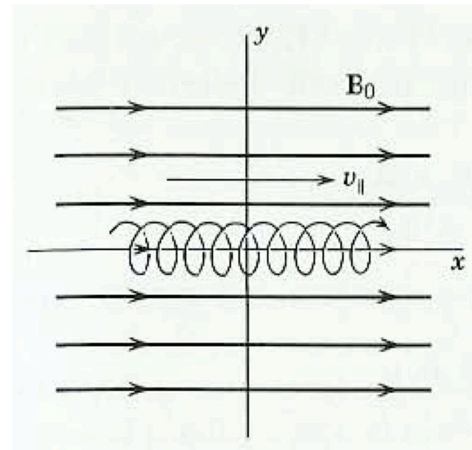
J.F. Wilkerson & HR

Cyclotron radiation from tritium beta decay

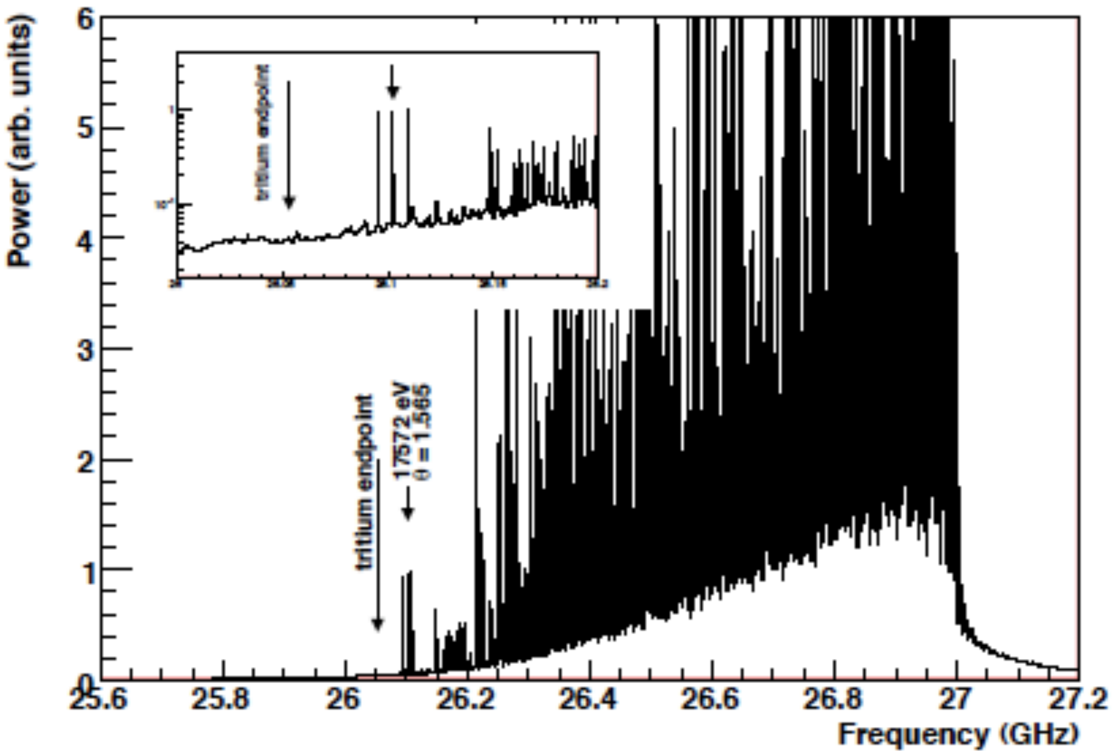
(B. Monreal and J. Formaggio, PRD 80:051301, 2009)

$$\omega = \frac{qB}{\gamma m} \equiv \frac{\omega_c}{\gamma}$$

$$\omega_c = 1.758820150(44) \times 10^{11} \text{ rad/s/T}$$



Radiated power ~ 1 fW

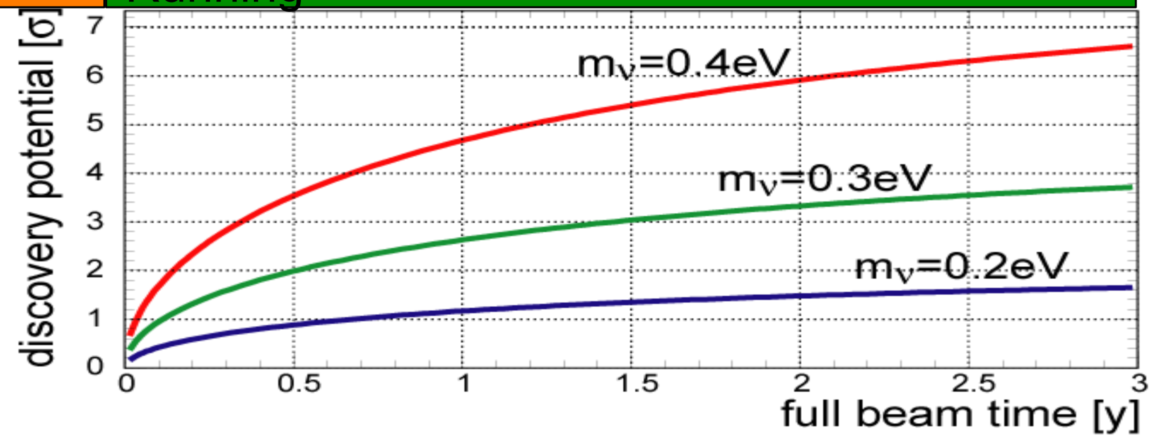


Parameter	Value	Unit
Electron energy	18.6	keV
β	0.2627	
γ	1.0364	
Field	1	T
ω_c	27.009	GHz

Neutrino mass: some milestones

Construction | Running

KATRIN:



Project 8:

Proof concept | Prototype | Phase I

Planck:

Analysis 1 | Analysis 2

2012 | 2013 | 2014 | 2015 | 2016 | 2017 | 2018

Who needs an underground lab?

We do.

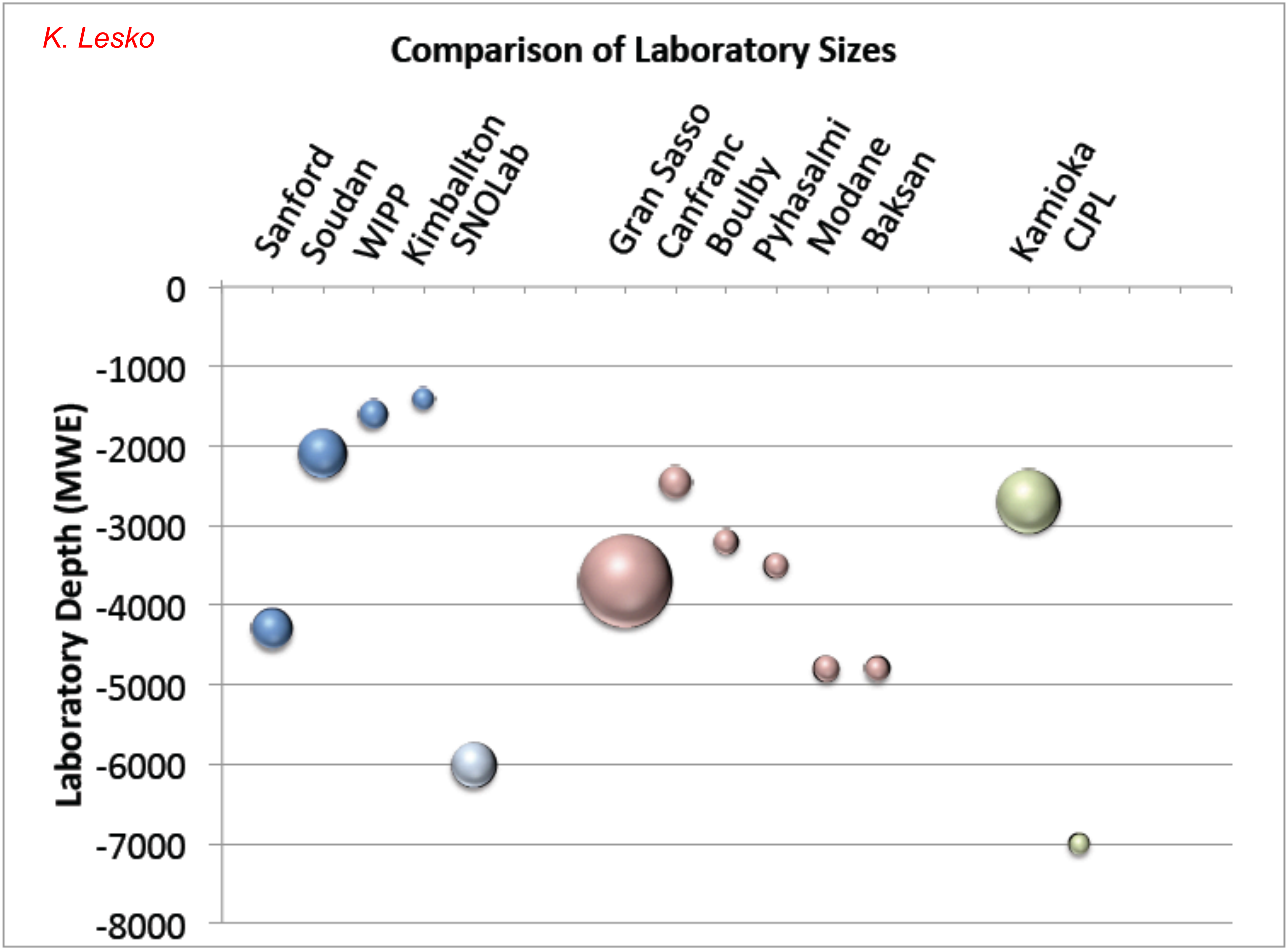
The US has been attempting to build a dedicated, deep underground lab since 1975. We did not get that (complicated history), but the science still needs to be done. SURF at Homestake is a new asset for us, a unique home for important parts of that science. It has attracted $70M in private funding, an extraordinary departure for nuclear physics.

Majorana (and LUX) are sited there, and smaller experiments. It's deeper than most national u/g labs, although probably not deep enough for the tonne-scale DBD expts. It's still very much a world-class facility, and, at last, we have "a bird in the hand".

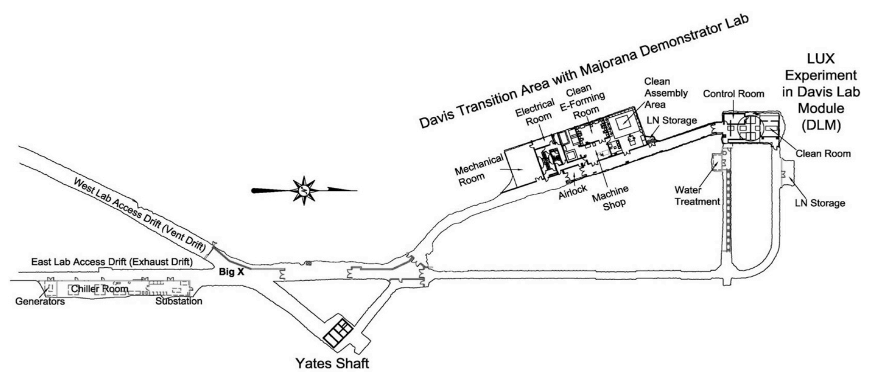
We will use SURF, WIPP, Soudan, Kimballton, SNOLAB, LNGS, Kamioka and we will do the science.

"…it was like stepping from a busy market into the quiet of a cathedral…"

Michael Moe


K. Lesko
Comparison of Laboratory Sizes
Sanford
Soudan
WIPP
Kimballton
SNOLab
Gran Sasso
Canfranc
Boulby
Pyhasalmi
Modane
Baksan
Kamioka
CJPL
Laboratory Depth (MWE)
0
-1000
-2000
-3000
-4000
-5000
-6000
-7000
-8000

Davis Campus at the 4850 level



Sanford Underground Research Facility SURF

Major objectives in Neutrino Physics

Known Unknowns

- $\cancel{\theta_{13}}$
- Hierarchy
- Mass
- CP violation
- Majorana or Dirac
- Relic neutrinos

Unknown Unknowns

- ~~OPERA~~
- N_ν ~ 4 from cosmology
- LSND, MiniBooNE
- Reactor anomaly
- Ga source anomaly

(DOE Nuclear Physics plays a strong role)

In search of the Hierarchy and δ_{CP}

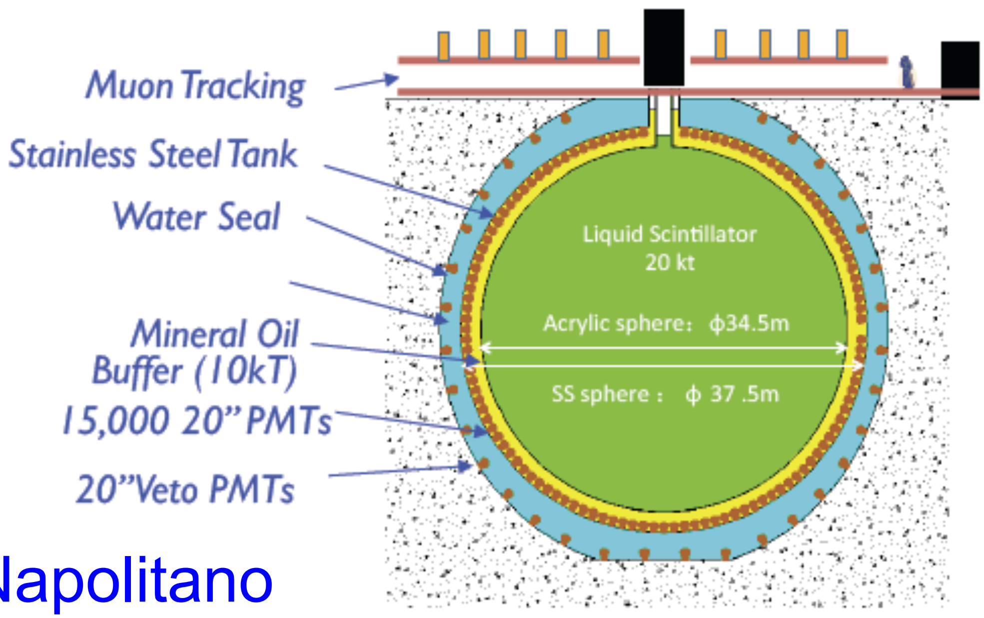
Experiment	$\nu_\mu \longrightarrow \nu_e$ Per Year	Background
T2K[a] *(Running)*	≈32	≈12
NOνA[b] *(Construction)*	≈23	≈11
LBNE[c] *(Proposed)*	≈40	≈6

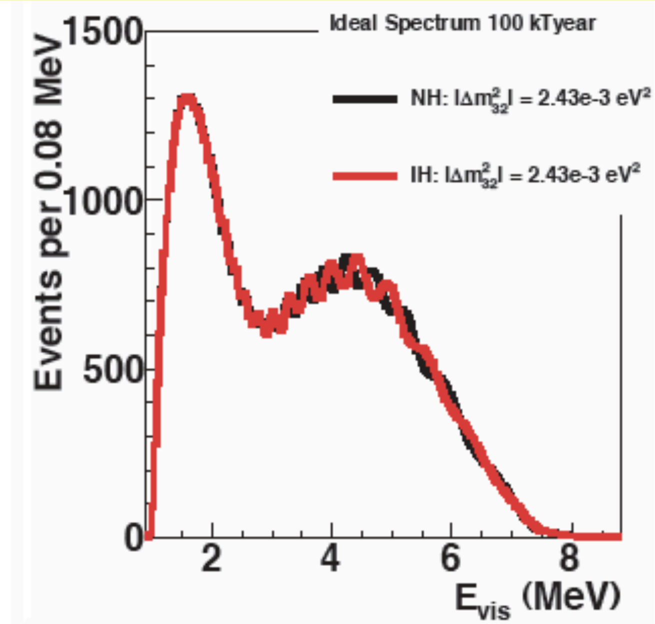
(a) 12×10^{20} protons-on-target in one year

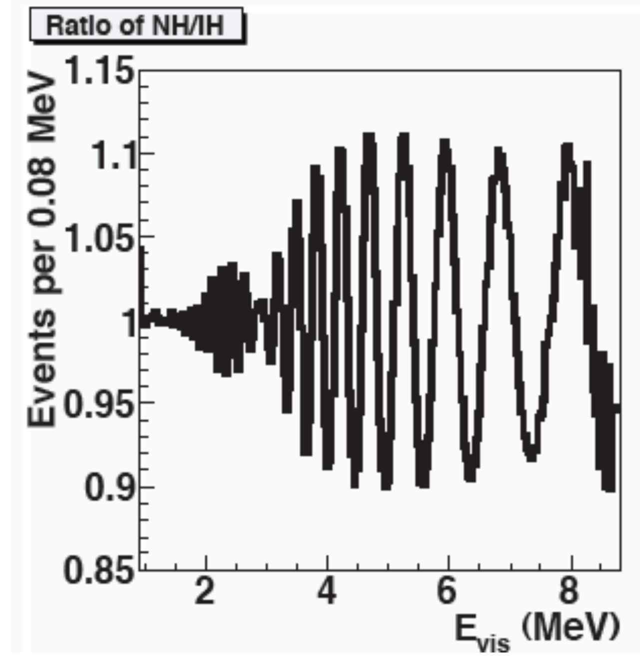
(b) 6×10^{20} (c) 6.5×10^{20} but ×3 larger w/ "Project X"

J. Napolitano

In search of the Hierarchy







J. Napolitano

The big questions

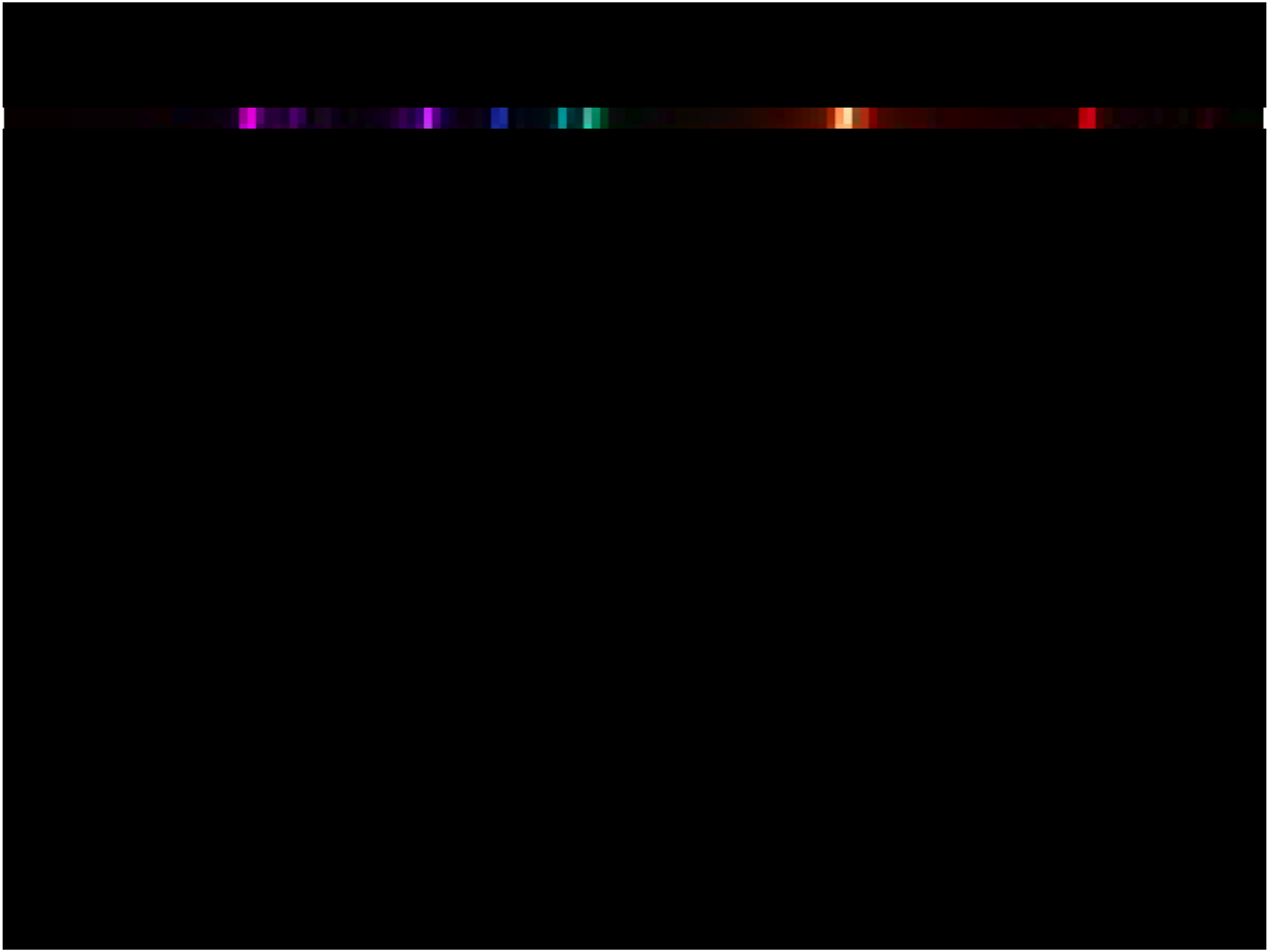
Compelling and unique science to be done in the next 5 years

- KATRIN mass measurement
- $0\nu\beta\beta$ searches: Ge, Te, Xe, Nd, …
- SNO+, Borexino: CNO, luminosity constraint tested

Vision for 2020 (2030 in neutrino units)

- Direct mass measurement to +/- 20 meV
- Neutrinos are Majorana [or Dirac]
- Hierarchy is Normal [or Inverted]
- CP violation is found in neutrino sector [or limited]
- Sterile neutrinos are found [or limited]
- Solar luminosity ratio (neutrinos/photons) measured to 1%

A very exciting future!



Large-scale experiments

Table 4. Details of the most advanced experiments. Given are life-time sensitivity and the expected limit on $\langle m_{ee} \rangle$, using the NME compilation from figure 5.

Experiment	Isotope	Mass [kg]	Sensitivity $T_{1/2}^{0\nu}$ [yrs]	Status	Start of data-taking	Sensitivity $\langle m_\nu \rangle$ [eV]
GERDA	^{76}Ge	18	3×10^{25}	running	~ 2011	0.17-0.42
		40	2×10^{26}	in progress	~ 2012	0.06-0.16
		1000	6×10^{27}	R&D	~ 2015	0.012-0.030
CUORE	^{130}Te	200	$6.5 \times 10^{26*}$	in progress	~ 2013	0.018-0.037
			$2.1 \times 10^{26**}$			0.03-0.066
MAJORANA	^{76}Ge	30-60	$(1-2) \times 10^{26}$	in progress	~ 2013	0.06-0.16
		1000	6×10^{27}	R&D	~ 2015	0.012-0.030
EXO	^{136}Xe	200	6.4×10^{25}	running	~ 2011	0.073-0.18
		1000	8×10^{26}	R&D	~ 2015	0.02-0.05
SuperNEMO	^{82}Se	100-200	$(1-2) \times 10^{26}$	R&D	~ 2013-15	0.04-0.096
KamLAND-Zen	^{136}Xe	400	4×10^{26}	running	~ 2011	0.03-0.07
		1000	10^{27}	R&D	~ 2013-15	0.02-0.046
SNO+	^{150}Nd	56	4.5×10^{24}	in progress	~ 2012	0.15-0.32
		500	3×10^{25}	R&D	~ 2015	0.06-0.12

W. Rodejohann, 1206.2560

International Context

KamLAND, SK, T2K in Japan

Daya Bay in China

SNO+, NeXT ? in Canada

KATRIN in Germany

CUORE in Italy

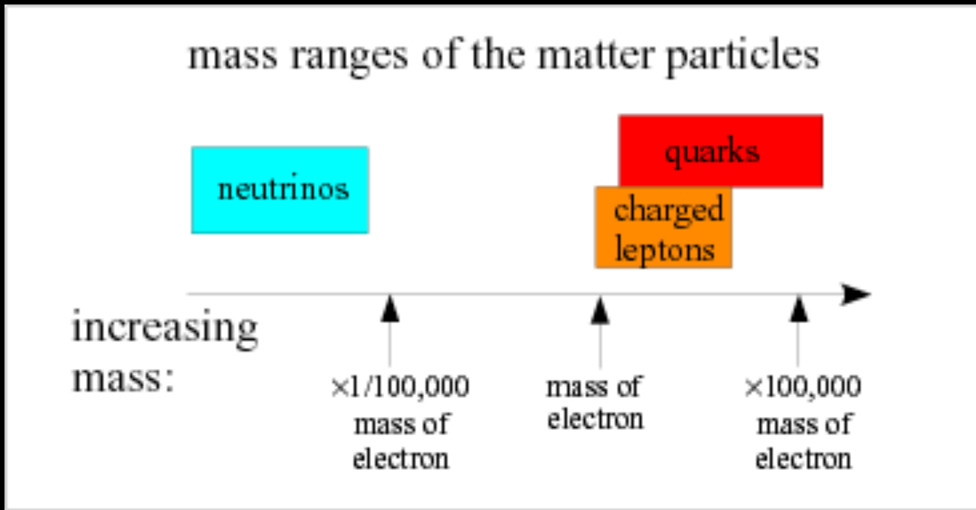
Majorana/GERDA will join forces for 1-T Ge. Is SURF 4850 deep enough, or will this go to Canada or China?

EXO-200, MINOS, MiniBooNE in US

nEXO probably in Canada

IceCube at the South Pole under US Administration

The cost and difficulty involved at the neutrino frontier makes international collaboration all but essential. But this should not exclude the possibility of doing *some* experiments in the US.

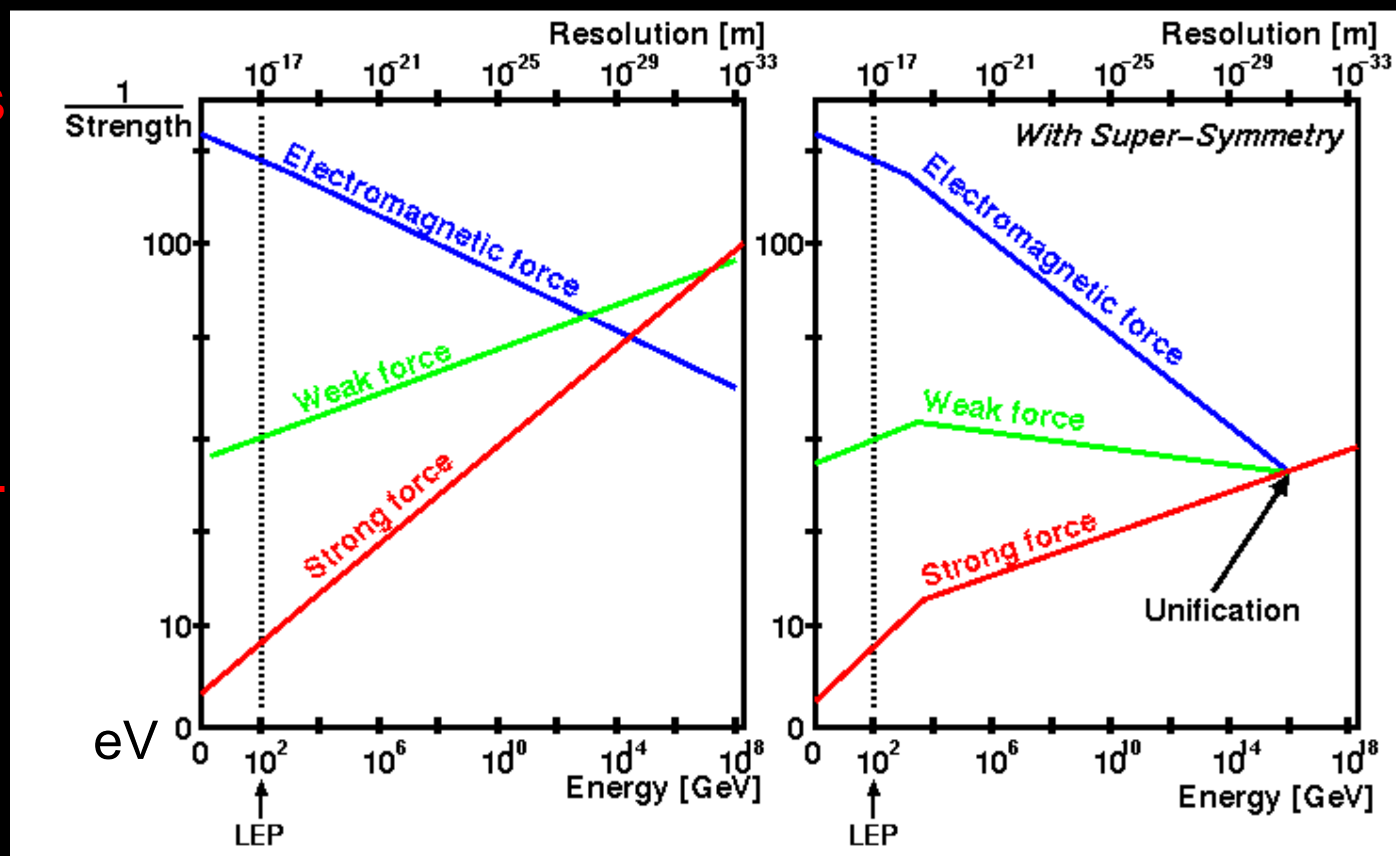


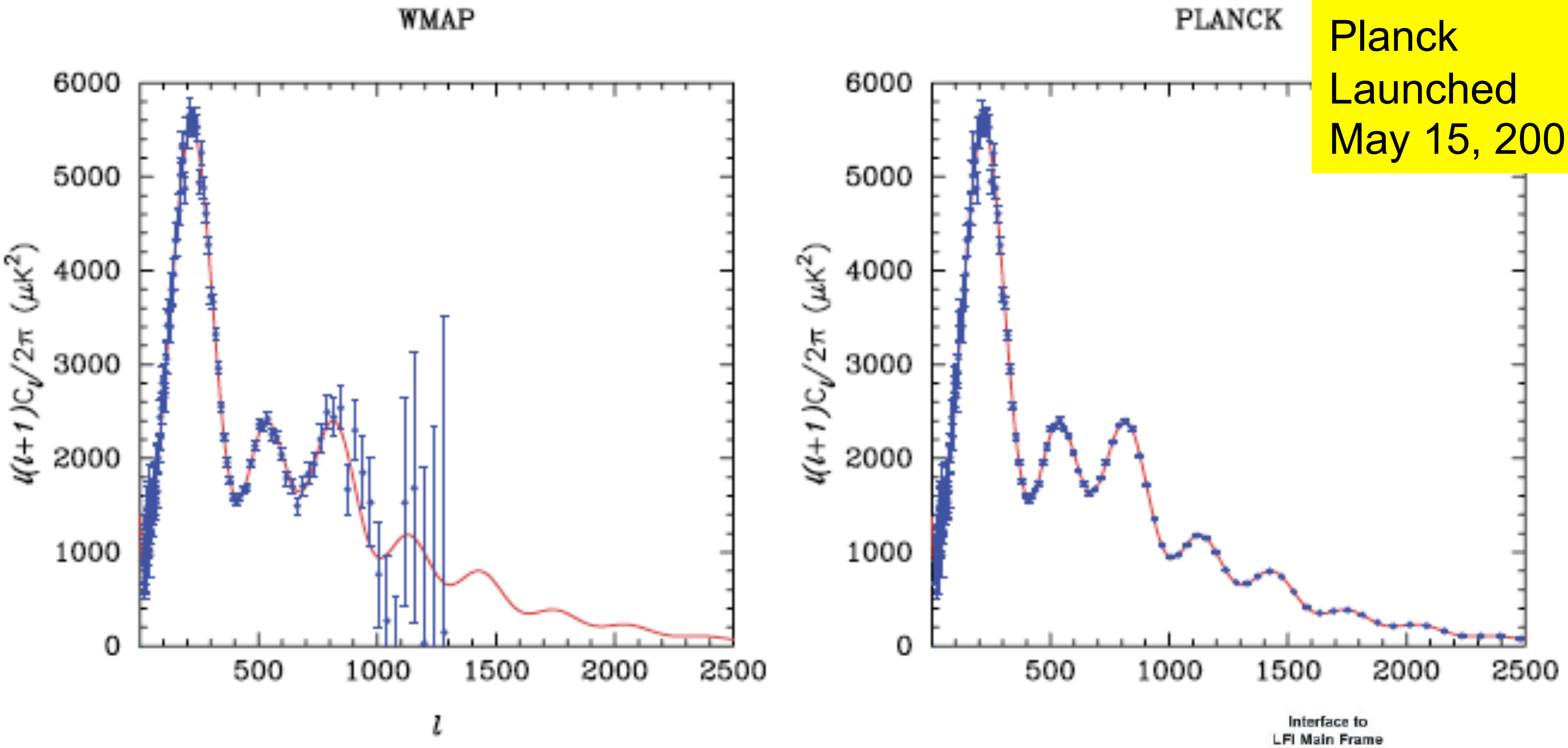
Why is neutrino mass so small?

Neutrino mass is not a feature of the SM

A signal of unification? See-saw model:

$$\boxed{m_\nu = \frac{m_D^2}{M}}$$



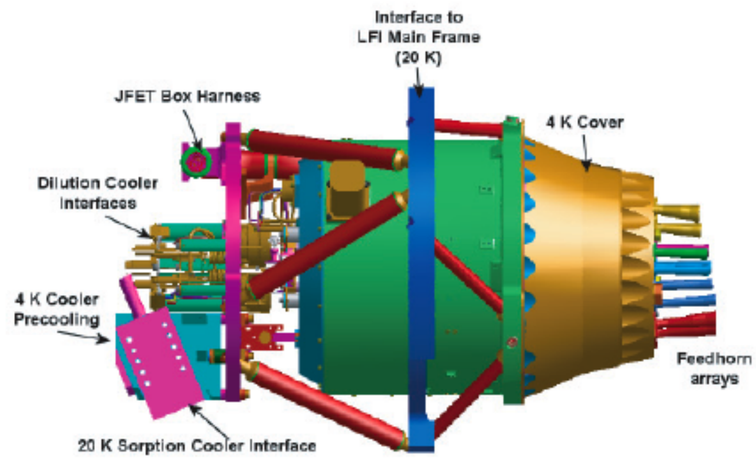


Planck
Launched
May 15, 2009

Present ΛCDM constraints on Σm_ν: ~ 0.6 eV

Planck sensitivity:

1. Planck only 0.26 eV
2. Planck + SDSS 0.2 eV
3. CMBR + grav. lensing 0.15 eV



From Planck “Bluebook”

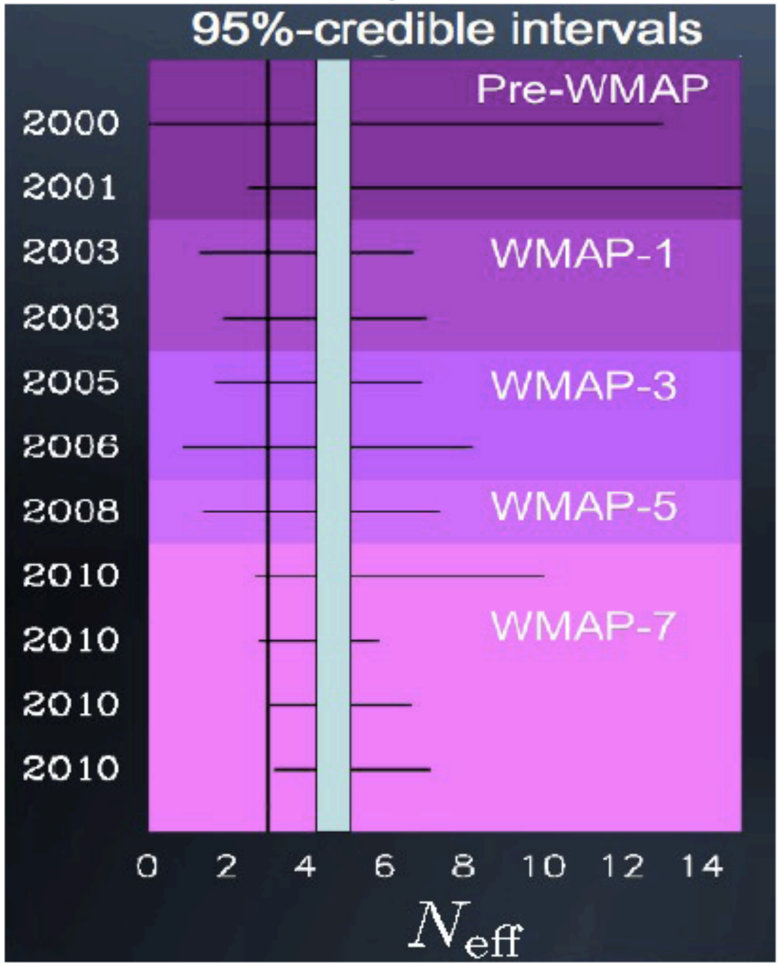
Recent hint for $N_{eff} > 3$ from precision cosmology...

- Parameterise excess relativistic energy density in terms of extra species of massless neutrinos.

$$\rho_\nu + \rho_X = \underline{N_{\text{eff}}} \left(\frac{7}{8} \frac{\pi^2}{15} T_\nu^4 \right)$$
$$= (3.046 + \Delta N_{\text{eff}}) \left(\frac{7}{8} \frac{\pi^2}{15} T_\nu^4 \right)$$

- **Evidence for $N_{eff} > 3$:**
  - @ 98.4% (CMB+LSS)
    Hou et al. 2011
  - @ 99.5% (CMB+LSS+BBN)
    Hamann et al. 2011

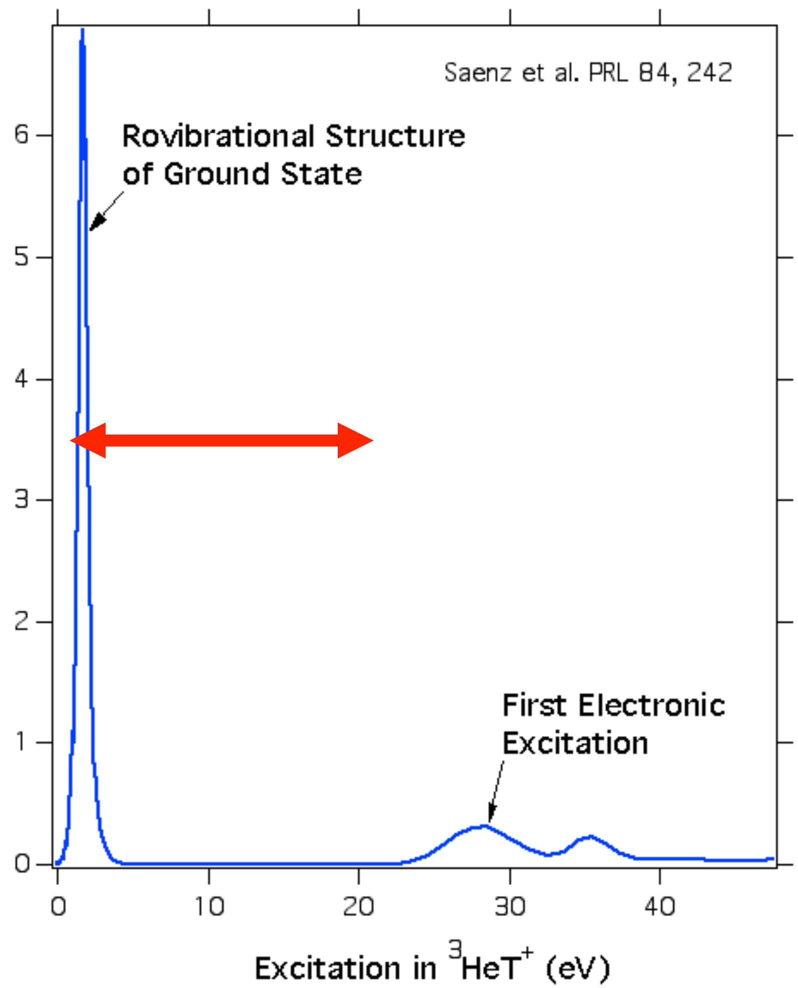
Adapted from S. Hannestad



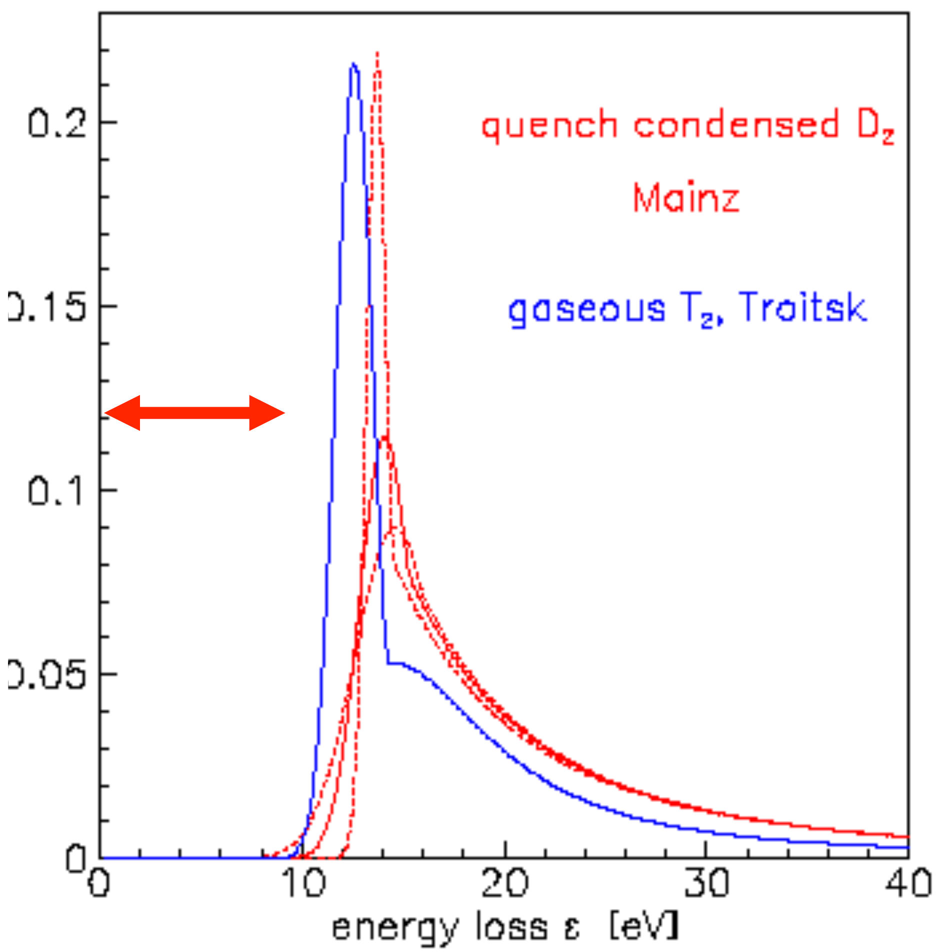
Y.Y.Y. Wong

A window to work in

Molecular Excitations

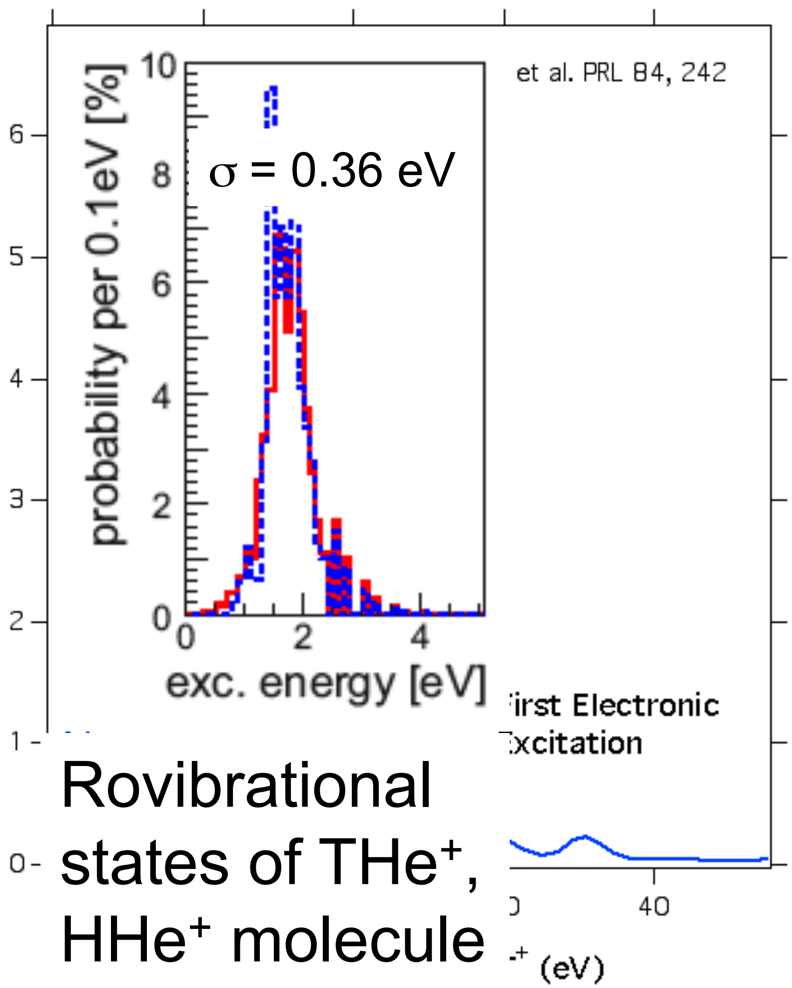


Energy loss function



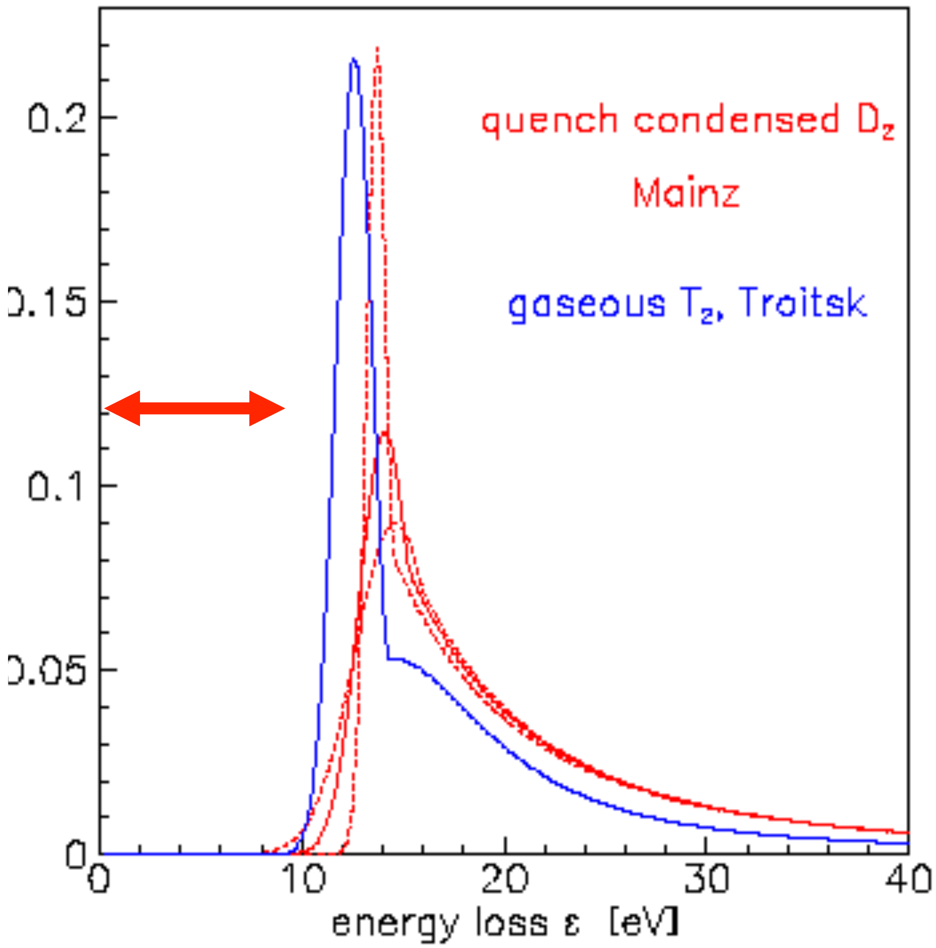
A window to work in

Molecular Excitations



Rovibrational states of THe^+, HHe^+ molecule

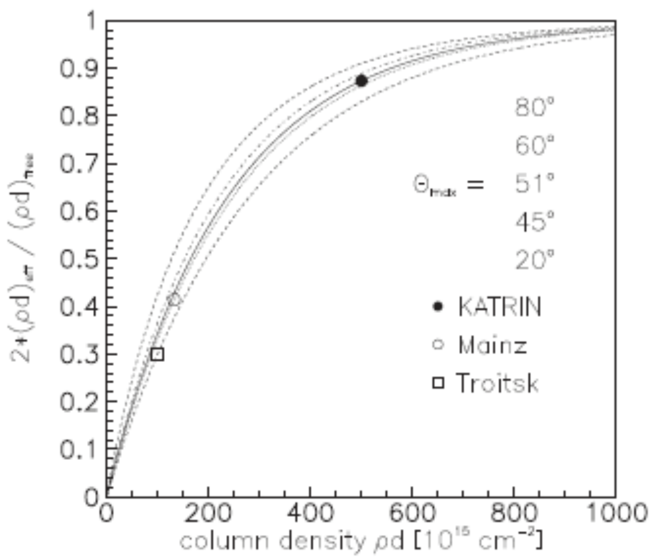
Energy loss function



The Last Order of Magnitude

If the mass is NOT in the 200-2000 meV window, but <200 meV, how can we measure it?

KATRIN may be the largest such experiment possible.

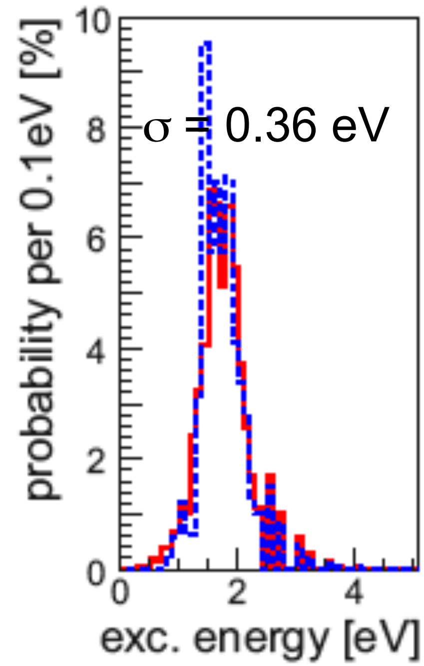


Source T_2 column density near max

Size of experiment now: Diameter 10 m.

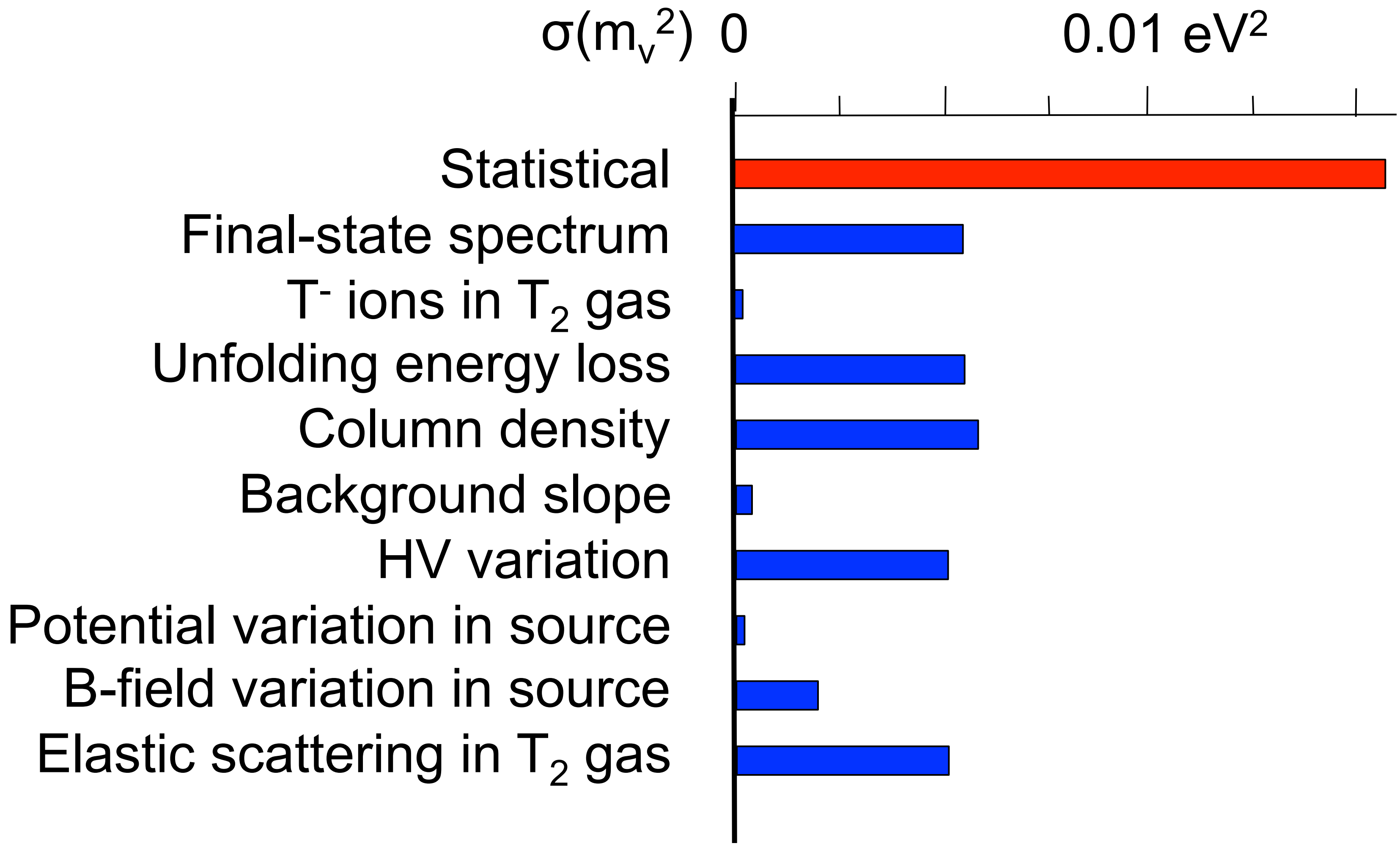
$$\sigma(m_\nu^2) = k\frac{b^{1/6}}{r^{2/3}t^{1/2}},$$

Next diameter: 300 m!



Rovibrational states of THe^+, HHe^+ molecule

KATRIN's uncertainty budget

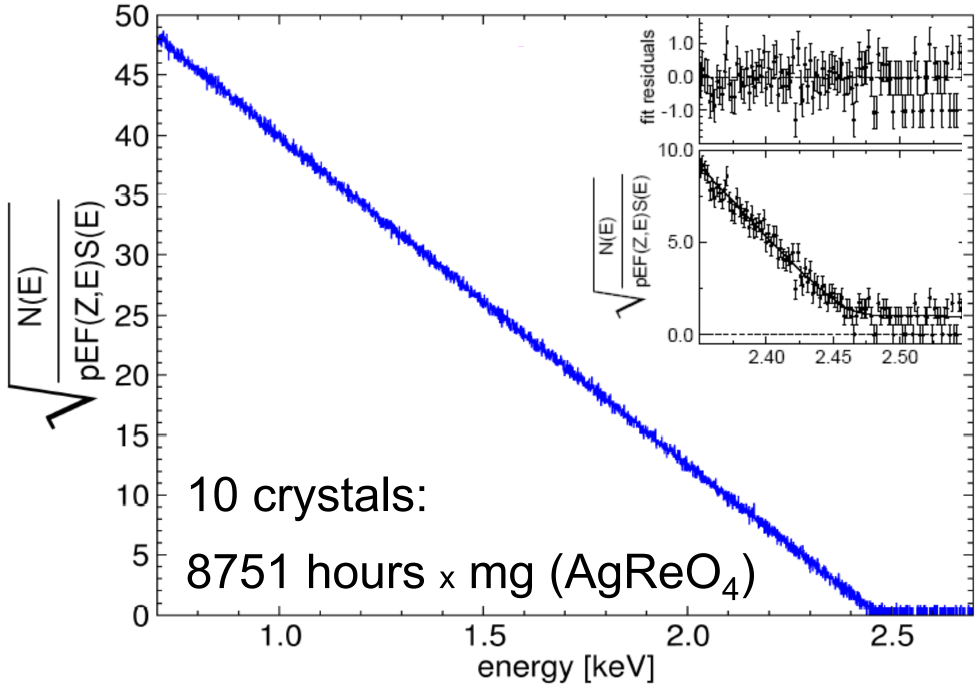


$\sigma(m_\nu^2)_{total} = 0.025\ eV^2$

$m_\nu < 0.2$ eV (90 % CL)

Microcalorimeters for ^{187}Re ß-decay

MIBETA: Kurie plot of 6.2 ×10^{6} ^{187}Re ß-decay events (E > 700 eV)



E_0 = (2465.3 ± 0.5$_{stat}$ ± 1.6$_{syst}$) eV

$\boxed{m_\nu^2 = (-112 \pm 207 \pm 90)\ eV^2}$

MANU2 (Genoa)
metallic Rhenium
m(ν) < 26 eV

Nucl. Phys. B (Proc.Suppl.) 91 (2001) 293

MIBETA (Milano)
$AgReO_4$
m(ν) < 15 eV

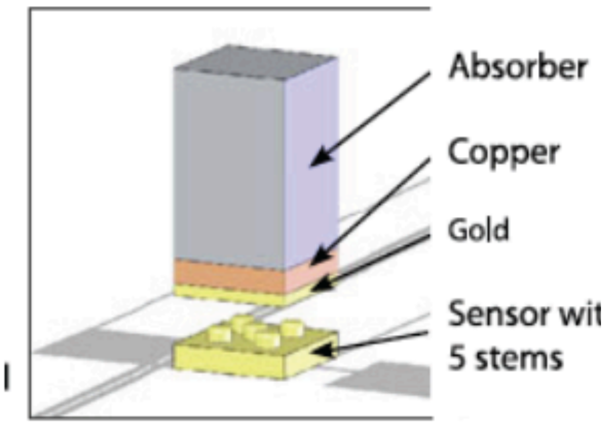
Nucl. Instr. Meth. 125 (2004) 125

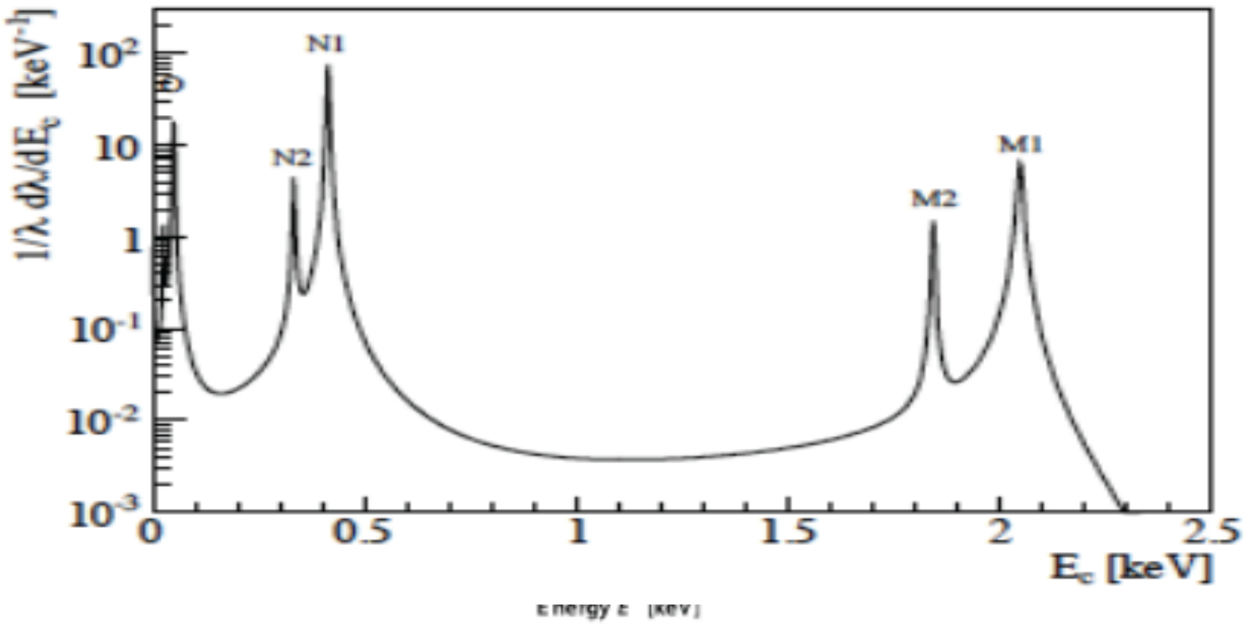
MARE (Milano, Como, Genoa, Trento, US, D)
Phase I : m(ν) < 2.5 eV

hep-ex/0509038

Electron Capture Holmium Expt (ECHO)

- Using low-temperature Metallic Magnetic Calorimeters to study both ^{187}Re and ^{163}Ho.
  - should be able to achieve ultimate resolution ~ 2 eV and rise-times of 90 ns



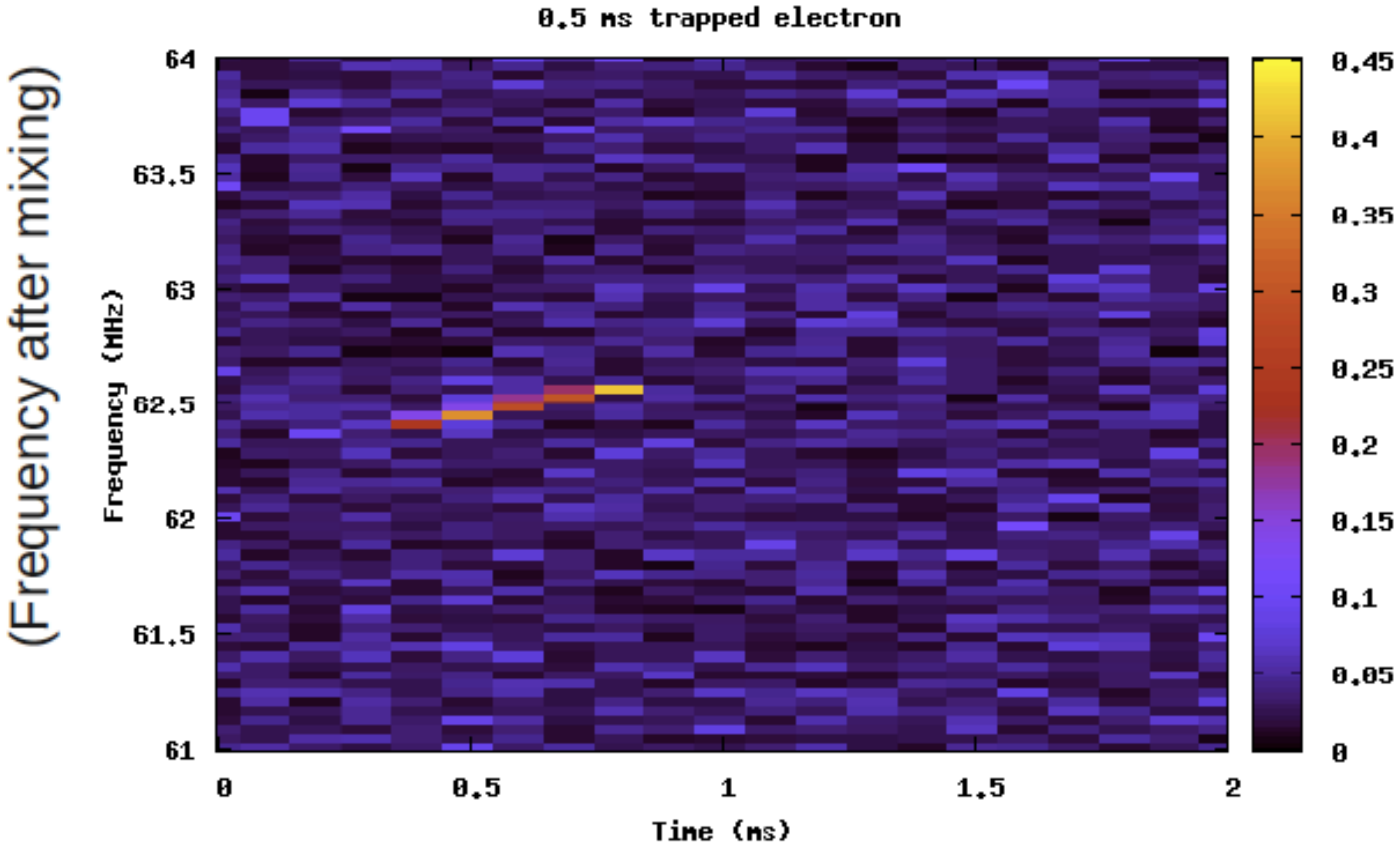


  - report Q_{EC} = 2.80 ± 0.16 keV
  - shapes of N and M lines not entirely understood

J.F. Wilkerson

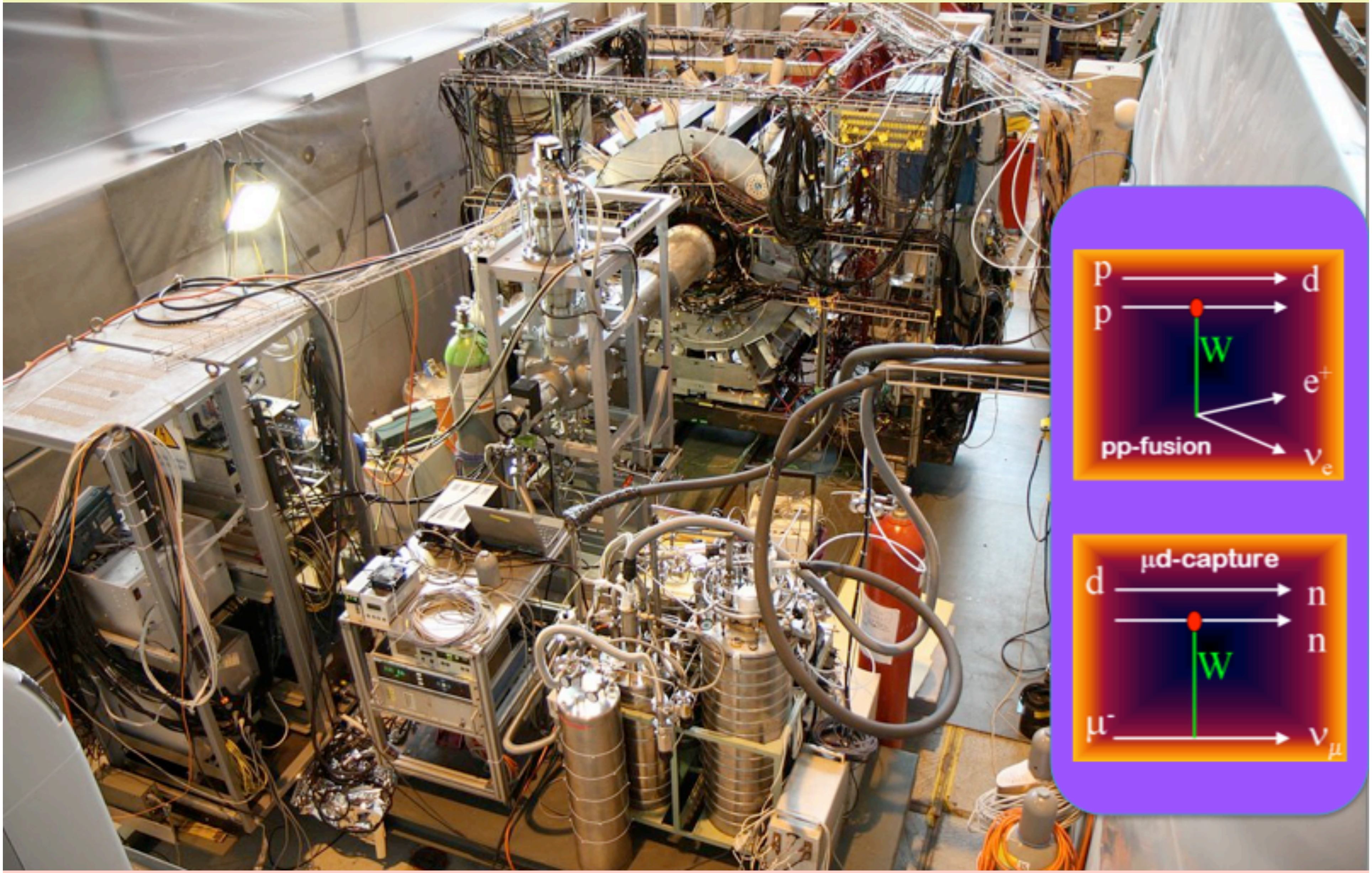
Signal is a rising "chirp" in frequency

Current detector simulation



simulation M. Leber

Calibrating the Sun & SNO – MuSun at PSI



P. Kammel

The MNSP Mixing Matrix and oscillations

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Unitary matrix: 9 parameters not all independent.

3 trig angles enough to describe oscillations. There are also CP-violating phase(s).

$$\nu_e = U_{e1}\nu_1 + U_{e2}\nu_2 + U_{e3}\nu_3$$

$$\lambda = \frac{h}{p} \qquad p_i - p_j \approx (m_j^2 - m_i^2)\frac{L}{2E}$$

Depends on **mass-squared differences × distance**, & the **sizes of the U_{ei}**